UNIVERSITY OF SOUTHERN QUEENSLAND

Faculty of Health, Engineering and Science

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Evaluation of strength characteristics of recycled bituminous pavement materials

A Preliminary Report submitted by

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Abstract

There is a long history of natural resources exploitation without accounting for their limitations. One of the greatest challenges is to find new ways of saving natural resources to create a long-term and stable green environment for generations to come.

Research in past decades has uncovered that reclaimed asphalt pavement (RAP) is a valuable part of hot mix asphalt. Primary reasons of using the reclaimed asphalt in asphalt pavements are both environmental and economic.

The key purpose of this project is to investigate the strength characteristics of recycled proportioned asphalt pavement materials through determining the resilient modulus of asphalt. Resilient modulus is an important design parameter for pavement structures, as it represents the structural strength of pavement layers through which the thickness design is based.

After reviewing past research and current Austroad practices, dense grade 20 (DG20) mix design prepared with 0%, 15%, 30%, 40%, 50% and 60% reclaimed asphalt-proportioned composition with C600 and C320 binder material formed the base specimens. To verify previous experimental work and current Austroad guidelines, the indirect tensile test method was used to determine the resilient modulus of the specimens.

After analyzing the results, it was concluded that with an increasing amount of reclaimed material, the resilient modulus also increased. This confirmed the results of previous studies. However, the resilient modulus for the 15% proportioned mix was very high and 40% RAP result was similar to 0% RAP, which did not comply with current guidelines. There was an initial concern to lower the binder grade as a lowered grade binder can

compensate the RAP aged binder. However, doing so comes at the potential risk of soft pavement production, which in turn could lead to an increased risk of rutting.

From the results of this study the Austroad guidelines, in their current form, are not sufficient to attain the best performance for high proportioned Reclaimed asphalt pavements materials. The major recommendation from these results is to conduct a larger scale experiment to find the optimal mix design of reclaimed asphalt and thus use these results to help inform a review of the current Austroad guidelines concerning such mixes.

Key Words

Reclaimed asphalt pavement (RAP), Hot-mix asphalt, Recycled Asphalt, Resilient Modulus, Indirect tensile strength, Fatigue life.

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ENG4111 Research Project Part 1
&
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Limitations of Use

Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, expect where otherwise indicated and acknowledged.

I further certify that the work ids original and has not been previously submitted for assessment in any other or institution, expect where specifically stated.

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Date:---

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Chapter-1 Introduction

1.1. Background

The increasing demand for materials to restore and maintain roads and the growing interest in sustainable and environmentally friendly materials have set the incremental trend toward the use of recycled materials in asphalt pavement. The major source of recycled material is the reuse of Reclaimed Asphalt Pavement (RAP).

Poon, Qiao and Chan (2006) maintain that the production of demolition and construction waste has been increasing at a gradual rate in recent years. The amount of landfill available to contain this material has been decreasing, and the need to find appropriate disposal locations has intensified (Kuo, Mahgoub & Nazef 2002). Bennert and Gucunski (2000) reported that recycling programs offer a viable solution and the use of these materials as recycled base course in new roadway construction has become more common in the last twenty years in USA, with some municipalities reporting as much as 400,000 tons of recycled materials used in this manner. Recycled roadway materials are typically generated and reused at the same construction site, providing increased savings in both money and time (Nataatmadja & Tan 2001). Guthrie, Cooley and Eggett (2007) also speculated that in some municipalities recycled materials costs less to use than conventional crushed-stone base material by as much as 30%. Despite the increased acceptance of recycled base materials, research concerning the mechanical properties and durability of such materials has been lacking.

Reclaimed Asphalt Pavement is removed or milled and reprocessed material which includes aggregates and bitumen binder. The main source of RAP is from full depth removal and milling of existing roads. Asphalt recycling can be divided into two main categories: in-place or in-plant. As the name suggests in-plant recycling takes place at an asphalt manufacturing plant. Neumann (2013) stated that the Recycled Asphalt

Pavement (RAP) must be transported from the job site back to the plant and thus it is more common in urban areas, where travelling distances are not so high. In-place recycling takes place on-site where the pavement is being milled. It is more common on rural roads, where transport costs for in-plant recycling would be high. However, mobile plants may be used on large rural projects, which may make it feasible to utilize in-plant recycling.

Holtz and Eighmy (2000) reported that in the US, about 33 million tons of reclaimed asphalt pavements are used per year for recycling purposes, which is about 80% of the total amount of reclaimed asphalt pavements collected from old bituminous pavements. Also, Ikeda and Kimura (1997) reported that in the year 1995, 20 million tons of recycled hot mix was produced in Japan, which represented 30% of the total hot mix production.

According to Excel Asphalt (2014), the total production of asphalt in Australia in 2012 was 8.84 million tonnes, and RAP represented only 0.53 million tonnes. These statistics show that the use of RAP was only 6.03% of total production. According to Australian standards just 15% of RAP is recommended in asphalt mix design and up to 30% is permitted with very strict controls whereas in practice incorporation of RAP up to 50% is possible.

It is clear from the above research that Australia lags well behind in the use of RAP in asphalt products. RAP offers a number of advantages: economic, environmental, societal and industrial. RAP reduces the demand of virgin materials and landfills: it saves disposal costs, energy, raw materials and is environmentally friendly. It therefore, represents a significant step forward for the Australian asphalt industry if it were to increase the use of RAP in asphalt mixture and be encouraged to do so.

1.2. Study Motivation and Problem statement

Engineers employ two types of natural resources: materials and energy. Since most resources are limited, the engineer must concern himself with the continual development of new resources as well as the efficient utilization of existing ones.

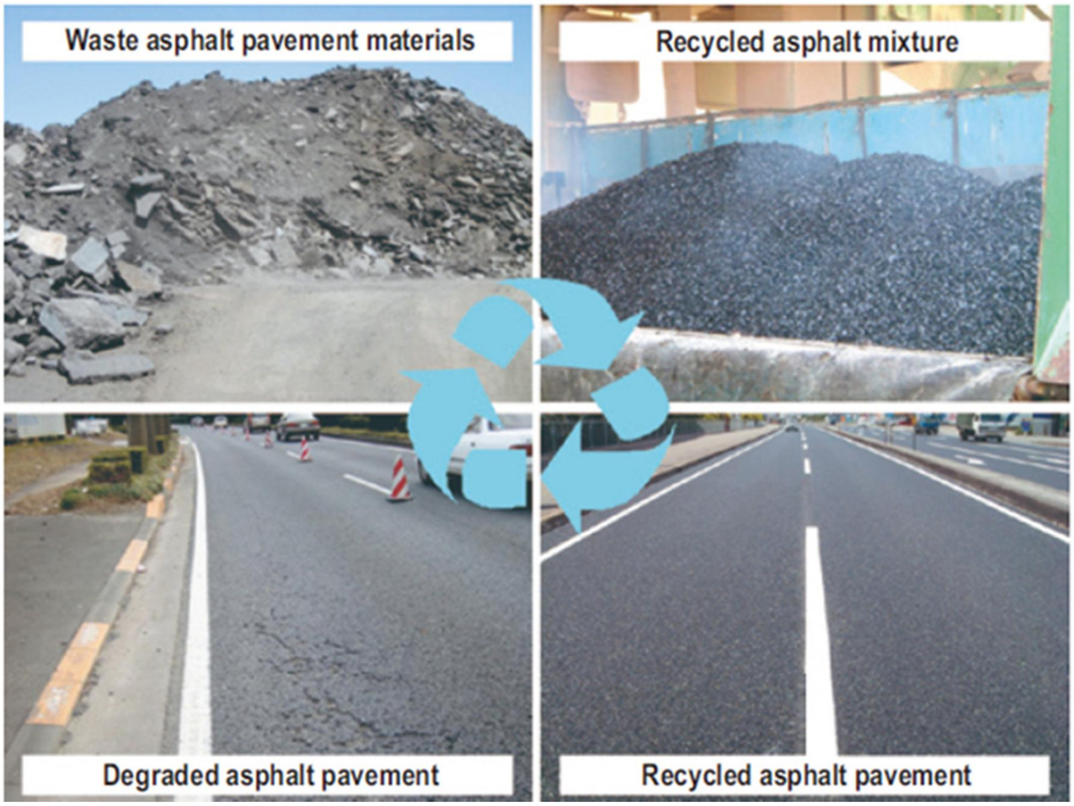

Figure 1: Asphalt pavement recycling circle
Source: Go Green < http://www.go-green.com.cn/>

As the scope of road works is increasing, the effort to explore a more diverse set of economical and environmentally friendly materials is building. The efficiency and performance of roads in accommodating a significantly increasing traffic volume in a safe manner is also of primary concern. At the same time, road departments are facing price increments of bitumen and aggregates - the basic ingredients of asphalt pavement. Reclaimed Asphalt Pavement (RAP) – the reuse of existing asphalt in various proportions in a final mix design - is one way of meeting these needs in a way that is cost effective.

Figure 2: The 100% Recyclable, Eco-Friendly Construction Material
Source: http://asphaltshinglegrinding.com/shingle_regrinding.html

While RAP may be a compelling addition to mix designs, it can affect the mechanical properties (Resilient Modulus) of asphalt. This in turn affects aspects such as reductions in asphalt ageing (in service); performance of pavement and vulnerability against fatigue cracking. Resilient modulus defines these properties of asphalt mixture and describes the stress-strain behavior of pavement asphalt under cyclic traffic load. Resilient modulus is an important parameter for flexible pavement design and evaluation. It is a significant factor in the design process of asphalt pavements, characterizing the performance of pavement structure. Therefore, it is the resilient modulus, which is the primary parameter of concern in this study: asphalt samples containing different proportions of old material will be tested to determine this parameter.

1.3. Study Objectives

The objective of this research study is to evaluate the role of Reclaimed Asphalt Pavement (RAP) and its effect on mechanical properties of asphalt containing different proportions of recycled asphalt and finally to compare the results of both mix designs to verify the current AUSTROADS specification.

The following objectives have been defined for this project:

- Background research about previously done experimental work for recycled asphalt mechanical properties.
- Review current AUSTROADS specification/standards in use for recycled asphalt pavement.
- Review and establish test methods for resilient modulus.
- Review mix design procedures and prepare samples containing various amount of recycled material.
- Define the test procedure and conduct laboratory tests to find out resilient modulus of various mix design.
- Analyze report and compare the results with the current AUSTROADS specification.

1.4. Overview of Dissertation

The following provides an overview of the dissertation as covered in the following chapters.

Chapter 2 RAP Source and Management

This chapter covers the source of recycled material, management of recycled asphalt material, current practices for recycling asphalt including in-place, in-plant methods and bitumen rejuvenation agents.

Chapter 3 Literature Review

This chapter covers the previous experimental work and research concerning the properties of recycled asphalt. This chapter describes the current Australian specifications for asphalt mix containing RAP materials.

Chapter 4 Preliminary Materials Tests

This chapter covers the test procedures used to evaluate the various parameters of virgin and RAP raw materials, used in mix design.

Chapter 5 Testing Methodology

This chapter describes the detailed procedure of mix design, test methods, volumetric properties, and prediction of fatigue life of pavement. This chapter provides details on how the resilient modulus of asphalt samples will be evaluated.

Chapter 6 Results and discussion

The outcomes of tests and resilient modulus of samples are provided in this chapter. The chapter also presents a discussion of test results and the summary charts.

Chapter 7 Conclusions and Recommendations

This chapter describes and summarizes the key findings of the project and presents conclusions with regards to current Australian guidelines for recycled asphalt pavement.

Chapter-2 RAP Source and Management

2.1. Reclaimed Asphalt Pavement (RAP) and Stockpile Management

The term, Reclaimed Asphalt Pavement (RAP) for removed or reprocessed pavement materials, this contains asphalt and aggregates. These materials are obtained during the asphalt pavements removal, reconstruction, maintenance, resurfacing. When removed material is crushed and screened properly, RAP consists of high quality, well graded aggregates.

The use of recycled asphalt pavement is growing in popularity, and as a result landfill space is being preserved. Reclaimed asphalt pavement is one way of optimizing the use of natural resources. It is an alternative source of materials that reduces reliance on virgin aggregate. The reduction of virgin materials usage in asphalt mix also has a flow-on effect in terms overall asphalt pavement cost. Thus, developing best practices surrounding the issue of increased reclaimed asphalt pavement content in asphalt pavement mixtures is of key concern.

The State Roads Agency (SRA) member of the Austroads Asphalt research Working Group (ARWG) has identified the issues regarding RAP and stockpile management. According to Austroads (AP-T286-15), most jurisdictional policies on RAP material management agree on the importance of:

- Maintaining consistency of stock materials
- Conducting routine quality control testing
- Preventing further contamination during storage.

2.2. Recycling Methods

General source of Asphalt pavement is either by milling or full depth removal. Milling is performed by construction equipment called milling machines or cold planers. These machines use a large rotating drum removing and grinding the road surface. The drum consists of scrolls of tool holders. According to Wikipedia 2015, the scrolls are positioned around the drum such that the ground pavement is moved toward the center and can be loaded onto the machines conveyor belt. Milling machine can remove up to 50 mm thickness in a single pass. Mostly the milled material hauled to a central facility for processing where it passes through different operations, like crushing, screening, conveying and stacking.

According to Kandhal et al. (1997), The Asphalt Recycling and Reclaiming Association (ARRA) define four different types of recycling method:

- Hot in-place recycling
- Cold in-place recycling
- Hot in-plant recycling
- Cold in-plant recycling

Figure 3: Asphalt Pavement surface milling with milling machine
Source: http://americanasphaltandmilling.com/v1/index.php/services

2.2.1. Hot in-place recycling

In this method pavement, area tended to be recycled is heated on a high temperature. It will help to remove the materials easily. Once the pavement heated, surface is scarified to the required depth. As per requirement fresh materials added. After well mixing the material it can be compacted to required thickness. As this process consumes less time, least disruption to traffic is caused. Also Jones (1979) stated that the transportation cost is less, as materials need not be taken away. Machinery required for this purpose being bulky in nature, sufficient right-of-way is required. This becomes an important consideration for in-place recycling within the city areas.

2.2.2. Cold in-place recycling

In this process, the pavement has scarified with a scarifier and crushed to required gradation. In this retreated process, milling the pavement up to required depth, crush the reclaimed material to the required size. Then the required amount of fresh materials in cold form (emulsion or cutback) is added. The material can be sprayed with bitumen emulsion many times. During, this process additives like, cement, quick lime, fly ash may be used. Mosey and Defoe (1979), stated that the cold mix recycling takes care of local geometric correction, correction of pavement distresses like surface cracks. If the existing road base is lacking in bearing capacity, then full depth reclamation can be done. Being an in-situ process the hauling cost is considerably low. Mallick (2005) described that the air quality related problems during construction are almost negligible as compared to hot mix process.

2.2.3. Hot central plant recycling

Hot central plant recycling takes place at factory central processing facility. RAP is collected by milling and crushed and screened to improve homogeneity. It is better to stockpiles the RAP of different mix designs and sources separately because their properties could be differ with each other. All material collected from stockpiles delivered to plant where RAP is mixed with required quantity of bituminous binder, fresh aggregates to start the process in hot mix plant. In the plant the material mixed thoroughly and heated to required temperature. At this point due to reheating further binder ageing accures, which can be minimized by devices such as the counter flow drum mixer and microwave heater. Neumann (2013) stated that the microwave heater works on the principle that more microwaves are absorbed by the aggregate than the bitumen, which reduces binder ageing, but requires much more electrical energy to operate. Nevertheless, these plant alterations can allow for RAP contents of up to 100% to be used.

When hot mix is ready then it has transported to construction site, where with paving machine or with other recommended methods, placed, and compacted to the required compaction level. The main advantage of this process is that the mix properties and performance is comparable to that of virgin mix (Wolters 1979). Epps et al. (1980) have noted that the quality control in this process is better when compared to hot in-place recycling. As RAP is susceptible to moisture, care needs to be taken while storing it. Less workspace is required for laying the recycled mix; hence this is suitable for the roads where the right of-way is somewhat restricted. However, Betenson (1979) reported that the RAP should not be exposed to extremely high temperature as it causes pollution due to smoke emission.

2.2.4. Cold central plant recycling

This process also takes place similar as the hot central plant mixing. The exception is only that there is no heating involve in this process, and therefore emulsion bitumen is used in most of the cases. Taking care of mixing time is primary component, so over heating may cause premature breaking of emulsified bitumen. Over mixing also can cause insufficient coating of aggregates.

2.3. Stockpiling Reclaimed Asphalt Pavement

Prevention and limitation of segregation is most important in RAP stockpiling. Uniformly layered stockpiles are preferred for storing loose RAP material which consists on various sizes. Reclaimed Asphalt Pavement material should stockpile in similar way of virgin material like cone style (natural angle) or in small heights piles with low sloped with satisfactory drainage as it could minimize the segregation. Austroads Guide to Pavement Technology (AGPT) part 4B states that Incoming RAP materials generally require crushing and/or screening to remove oversize materials and break up agglomerations in order to ensure a consistent grading and provide a free-flowing product. Separation into different-sized fractions further assists control of combined grading of the asphalt mix. It could be best practice to stockpile separately each source of RAP according to size of particles, quality of the aggregate, quantity of asphalt binder and category of mix design. These measures can maximize the percentage of RAP in asphalt mix design.

Figure 4: Typical RAP Stockpiling
Source: https://www.fhwa.dot.gov/publications/publicroads/10mar/06.cfm

During the stockpiling, space restrictions must need to consider. Stockpiles should need to keep clean and need to ensure that no any other types of material mix in RAP. RAP does not drain water like an aggregate stockpile do, so such arrangements need to establish to limit the moisture content.

To limit the moisture content a number of measures can be taken, such as storing RAP on solid sloped surface, covering with waterproof sheet, or with a roof from an open sided building. High moisture content in the stockpile affects the hot mix asphalt quality, as fine RAP has high moisture content, it could cause high level fuel usage and decreased production rate. A crust formed on the surface of stock pile which can be 200-250mm thick, which can be broken with the front end loader, but need to avoid the heavy machinery driven on RAP stockpile so stockpile should not compact.

According to Austroads (AP-T286-15), the Department of State Growth in Tasmania and the Department of Transport and Main Roads Queensland (TMR) have very similar specifications for RAP stockpile management. They both state that RAP material shall be processed to a well-graded, free-flowing and consistent product, and that the maximum aggregate size must not be greater than the aggregate size of the asphalt mix being produced. Both agencies also state that the RAP shall not contain tar binder and shall be free from deleterious materials.

The Department of Infrastructure, Energy and Resources specification G7 – Asphalt Production (DIER) 2012, states that separate stockpiles of RAP shall be placed prior to use and these stockpiles are to be tested for consistency in grading and binder content at a frequency of one test per 500 tonne of RAP. TMR specification MRTS30 (TMR 2010) states that processed RAP shall be stockpiled, and it also provides grading limits for the combined aggregates, filler and RAP, as well as the binder content of the design mix including RAP.

2.4. Rejuvenated bitumen binder

The ageing of the bitumen is the main problem in the use of recycled asphalt pavement (RAP) material in hot mix asphalt, which limits the percentage of applied RAP in hot mix asphalt. So, the rejuvenation of bitumen binder is the main and most costly part of recycling. The Austroads (AP-T18-02) framework for specifying asphalt states that caution must be used in determining targets for blending of binders, as fresh binder or rejuvenator may not be fully combined with the aged binder during the asphalt manufacture process. Consequently, mix performance characteristics imparted by binder stiffness, particularly fatigue and rutting resistance, may be somewhat intermediate between that of the fresh binder and that predicted from the stiffness or viscosity calculated or determined by extraction and testing of the blended binder.

Bitumen ageing depends on climate, bitumen composition, as well as pavement structure. The primary reason of ageing is the loss of volatiles and oxidation. Aged bitumen is stiffer, has higher viscosity and noticeable change in composition than fresh bitumen. In the result of this variance, adhesion loss and brittleness can occur. As bitumen becomes more aged and brittle, surface raveling and cracking, especially reflective cracking may occur. According to various investigations, the binder and aggregate from old hot mix asphalt are still valuable even their life cycle has ended. It is suggested that up to 15% RAP (without changing the grade of the added virgin binder) could be successfully used in superpave mixtures, while for the application of 25% RAP in Hot Mix Asphalt (HMA), a rejuvenators and softer binder should be used for aged bituminous binder. Investigations showed that using 19% rejuvenator (by weight of the bitumen) in the RAP, if designed and properly used, made application of recycled mixtures containing 80% RAP possible (Hallizza et al. 2011)

According to Austroads (2009), adding a bitumen that is one grade softer than that otherwise specified, where a mix contains 20-40% RAP. To obtain the softer bitumen, cutbacks, bitumen emulsion, foam bitumen may be added to lower the viscosity of the aged binder. Asphalt flux oils, lube stock, crankcase oil and slurry oil can be added as softening agents. It is also reported that a mixture of 80% aged bitumen with 20% recycled motor oil as a rejuvenator, obtained exclusively form waste materials, change aged bitumen that can have similar properties as new 60/70 bitumen. Furthermore, using rejuvenator agents such as lube extracts and extender oils may be used to reduce the mixing temperature, compaction temperature and to restore the physical and chemical properties of the aged bitumen.

Carpenter and Wolosick (1980) states the relation between the RAP binder and rejuvenator, in the beginning the rejuvenator develops a low viscosity cover around the RAP aggregate, slowly rejuvenator starts to penetrate in the RAP aggregate binder cover and melt the aged binder. As a result aged binder around RAP aggregate becomes softer. Once the aggregate free from rejuvenator, the penetration still continues and through the gradual process inner layer viscosity decrease and outer layer viscosity increase until the equilibrium is approached and blends stabilizes.

The rut resistance and stiffness of the mix decreases during this process until the blend stabilization. However, the fatigue resistance increases through this process. Carpenter and Wolosick (1980) suggested taking into account these effects during the mix design preparation. During conventional asphalt mixes without RAR, initially rut resistance is lower and increases as the binder ages and the fatigue resistance reduces as the binder hardens. Oliver (2001) reported that, for a mix containing 50% (artificially aged) RAP material, the modulus and rut resistance were lower than that of an equivalent mix containing only virgin materials. So it means the rejuvenator did not promptly complete mix with the RAP and creates low viscosity regions. This issue perhaps may less effect at lower percentages of RAP. It can be concludes that during the mix design preparation mix containing RAP and rejuvenator may not at first act as expected from blended binder properties because of the time needed to complete the dispersion process.

Austroads (AP-T286-15) reported that according to the European material specification for reclaimed asphalt EN 13108-8:2005, the penetration value of the RAP binder may be declared as grade P15 bitumen, provided that the mean of the penetration measurements is at least 15 d mm and that each measured penetration value is at least 10 d mm. Alternatively, the RAP binder may be classified as S70 bitumen, provided that the mean softening point is below 70 °C and all softening point measurements are below 77 °C. In other cases, the mean penetration value or mean softening point value shall be used to classify the RAP bitumen.

Chapter-3 Literature Review

3.1. Effects of RAP on volumetric & mechanistic properties of Asphalt Mixtures

Volumetric properties play an important role in the performance of asphalt mixtures. Volumetric values for 25% and 40% RAP mixtures are higher than processed RAP mixtures compared to control and 15% mixtures. Swamy et al. (2011) found that up to 15% addition of RAP does not have a noticeable effect on volumetric properties of the mixture, but as the amount of RAP increases, the voids in mineral aggregate (VMA) both increased as well as decreased in the samples. This statement adds further weight to Solanki et al.'s (2012) statement that the addition of RAP content from 25% to 40% gives 1.7% to 6.4% increased VMA. The variation in VMA is caused by insufficient blending of aged binder with virgin binder due to the heating time of materials. This shows that RAP from 15% or even up to 20% does not have a significant impact on important mix properties but once the addition percentage increases by 20% or more then there is a need to investigate the effects on properties of mixture.

Daniel and Lachance (2005) stated that the complex modulus of the asphalt mixtures with RAP increased from the control to 15% addition RAP level, whereas the asphalt mixtures added with 25% and 40% RAP had complex modulus curves same as 15% added asphalt mixture for both tension and compression, which was an unexpected result. The similar results were found in creep compliance curves. These trends were identified because of volumetric properties, asphalt content, and combination of gradation.

Swamy et al. (2011) also reported that with the increment of RAP addition up to 25% increased the average complex modulus curve and strength and then it started to decrease. Solanki et al. (2012), also validated these trends where complex modulus curve for 40% RAP was up to 81% higher than the 25% RAP added mixture.

Furthermore these can be verified from Shah et al. (2007) where reported that the results from complex modulus testing showed no increase in stiffness with the addition of 15% RAP compared with the control mix. However, the addition of 25% and 40% RAP resulted in an increase in the modulus. Li et al. (2008) also stated that hot mix asphalt containing 40% RAP found higher or similar modulus compared to asphalt mixtures with 20% RAP.

Goh and You (2008) found during the pavement rutting investigation that modulus increased with compaction to 4% air voids for more than 15% RAP contents. However, there was not significant variance for compaction up to 7%. So up to 7% air voids may not effect significantly and adding RAP percentage related to the level of compaction, same time level of rutting decreased by 24% during a physical test. Gardiner and Wagner (1999) also described that RAP contented mixture decreased the rutting but increased the potential for low temperature cracks. They also noted that increased RAP content was accompanied by an increase in tensile strength ratio. Huang, Shu and Vukosavljevic (2011) also found increased resilient modulus and decreased fracture energy with increased RAP during crack resistance test of hot mix asphalt. This investigation indicates the better resistance to permanent deformation in of rutting resistance.

3.2. Resilient Modulus

Resilient Modulus is a property of pavement material characterizing the elastic behavior under dynamic repeated loading. It is a measure of subgrade material stiffness. A material's resilient modulus is actually an estimate of its modulus of elasticity (E). While the modulus of elasticity is stress divided by strain for a slowly applied load, resilient modulus is stress divided by strain for rapidly applied loads like those experienced by pavements (Pavement Interactive 2007). The AASHTO Pavement Design Guide (1993), in addition to other revisions, incorporated the resilient modulus (MR) concept to characterize pavement materials subjected to moving traffic loads.

It is defined as the ratio between deviator stresses to recoverable strain. Huang (1993) described that if the load is small compared to the strength of the material and is repeated for a large number of times, the deformation under each load repetition is nearly completely recoverable and proportional to the load and can be considered as being elastic.

Rahim (2005) stated that under repeated load tests, it is observed that as the number of load cycles increases, the modulus increases. After a number of load cycles, the modulus becomes nearly constant, and the response can be presumed to be elastic. This steady value of modulus is defined as the resilient modulus.

Asphalt specimen when placed under a repeated load, in the beginning of load application a noticeable plastic strain noted. As the repeated load cycles increases, the plastic strain caused by each load repetition decreases. As the figure is showing that after 100 to 200 cycles, almost total strain is recoverable.

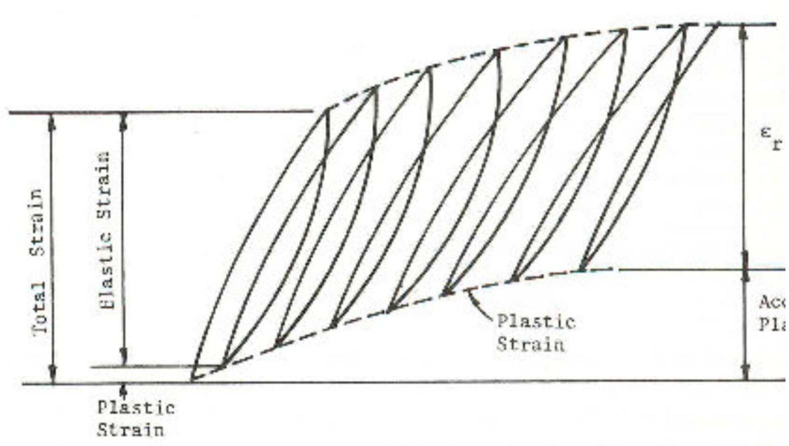

Figure 5: Strains under repeated load
Source: Yang and Huang 2004, pp. 280

Consequently, the elastic modulus is on strain recovery bases, characterized as the resilient modulus, which is axial or deviator stress over the recoverable strain. Under the repeated load the resilient modulus is determined by the following equation:

$$M_r = \frac{\sigma_d}{\varepsilon_r} \qquad (1)$$

$$\sigma_d = deviator\ stress$$

$$\varepsilon_r = Resilient\ strain$$

Katicha (2003) stated that as the applied load mostly small compared to the strength of specimen so, the same specimen can be used for same test under different loading and temperature.

3.2.1. Resilient Modulus determination

The resilient modulus test is the most common method of determination of stiffness modulus for hot mix asphalt. It includes setting up a compacted cylindrical shaped asphalt specimen which is subjected to repeated loading. There are two sections to the testing methods; the preconditioning and test setting determination, and the resilient modulus determination.

For the preconditioning and test setting determination, it is necessary to specify the range of recovered horizontal strain and the peak load which required to deforming the specimen within that range. Recovered horizontal strain can calculate by following equation:

$$P_e = \frac{ED\varepsilon h_c}{(v + 0.27) * 10^6} \qquad (2)$$

Pe = estimated peak load (N)

E = estimated resilient modulus of the specimen (MPa)

D = average diameter of the cylindrical specimen (mm)

hc = average height of the specimen (mm)

ε = recovered horizontal strain (με)

υ = Poisson ratio (estimated as 0.4)

For resilient modulus determination, follow above preconditioning procedure and with specified time intervals apply five load pluses to the peak load determined from before, measure and record the recovered horizontal deformation after every pulse. The following equation can determine the resilient modulus:

$$E = \frac{P(v + 0.27)}{h_c H} \qquad (3)$$

E = resilient modulus (MPa)

P = peak load (N)

v = Poisson ratio (assumed as 0.4)

H = recovered horizontal deformation of specimen (mm)

hc = height of specimen (mm)

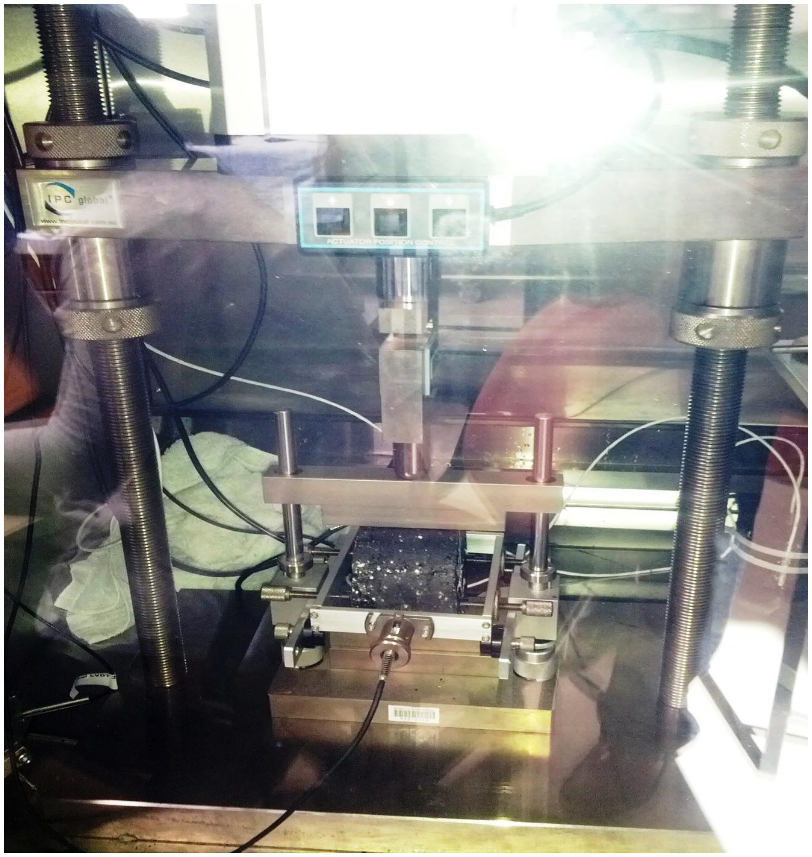

Figure 6: Matta testing machine for indirect tensile strength

The value of resilient modulus indicates the stiffness of the asphalt mixture or prepared specimen. Stiffness of pavement directly linked with rutting and fatigue age of asphalt pavement. The high value of resilient modulus indicates the stiffness, which means that traffic load will transfer on wider area. Stiffer pavement has more resistance against permanent deformation, which is an advantageous for rutting resistance and protects weak subgrade layers. However stiffer pavement is susceptible to fatigue cracks, which minimize the pavement age. Therefore resilient modulus for different percentages of RAP can help to determine an optimum balance mix design to maximize the pavement age.

3.2.2. Factors Affecting Resilient Modulus

Resilient modulus is an important property for asphalt mix design and mechanistic analysis of pavement response under traffic loads, environmental effects. There are many types of factors that can impact the determination of the value of resilient modulus. These factors include the geometric factors of test specimens, size of aggregates, load waveforms type of compaction and pulse duration selection. This is very necessary to control these parameters to get consistent results.

Su (2006) stated that Investigations indicated that the maximum nominal aggregate size has the most influencing factor on the resilient modulus, followed by load duration, specimen thickness, and specimen diameter. Diameter-Aggregate size interaction was the most significant 2-level interaction, while the most significant 3-level interaction was the diameter-thickness-aggregate size interaction. This statement indicates that geometry of the specimen size for a resilient modulus is critical factor. The indirect tensile testing method describes that diameter of the specimen to be either 100 mm or 150 mm to determine the resilient modulus of an asphalt mix.

The Australian Standard AS2891.13.1 states that test specimens containing maximum particle size of up to 40 mm can be used for the resilient modulus test. However, the interaction of the aggregate size with other factors is not known. Another investigation by Lim and Tan (1995) stated that the resilient modulus decreases as the diameter or maximum nominal size ratio increased. These statement shows that higher resilient modulus would be achieved if a small diameter use to test large top stone size.

Brown and Bassest (1990) conducted a research on finding the relationship between maximum aggregate size and asphalt mix properties. They found a good correlation between the resilient modulus and the maximum aggregate size. As the aggregate size increased the resilient modulus increased as well. In addition, a resilient modulus increased by 53%, 107% and 93% measured when testing temperature was at 5°C, 25°C and 40°C respectively.

Neumann (2013) states that Austroads (2012, p.65) has published a table that indicates the effect of particular factors on resilient modulus. The most these elements will be controlled for every test, like temperature and rate of loading. Temperature and rate of loading both have a significant impact on the resilient modulus. However, asphalt mixture properties like density are likely to fluctuate depending on the percentage of RAP added and the density of those aggregates relative to the virgin aggregates.

Significant variance in density, binder ageing, bitumen viscosity and air voids is expected for mix designs consist more than 20% RAP. So these investigation states that binder ageing is not only the reason of change in resilient modulus, mix design gradation improve the performance of asphalt pavement.

Table 1: Factors affecting modulus of asphalt and effect of increasing factor values
Source: Austroads 2012, p.65

Factor	**Effect of Increasing Factor**
Proportion of coarse angular particles	Increase
Density	Increase
Stress level	No change
Age	Increase
Extent of cracking	Decrease
Efficiency of mixing	Increase
Bitumen content	Increase then decrease
Bitumen class	Increase
Bitumen viscosity	Increase
% Air voids	Decrease
Temperature	Decrease
Rate of loading	Increase

3.3. Current Austroads Specifications for Recycled Asphalt Pavement

Current specifications for recycled asphalt pavement are not same in all over the Australia. Department of Transport and Main Roads Specification PSTS109 Reclaimed Asphalt Pavement Material (AAPA-2014) state the conformance requirements in clause 7, 8 and 9.

3.3.1. Materials

RAP material must comply with the following requirements:

a) It must be sourced totally from asphalt and must not contain any foreign materials such as road base, concrete, coal tar, plastics, brick, timber, scrap rubber etc as defined in Test Method RMS T276, and must be free from dust, clay, dirt and other deleterious matter.

b) The aggregates must conform to the requirements of Tables 7.1 and 7.2 of PSTS108 Aggregates of Asphalt. The particle size distribution and material finer that 75 µm must be determined on the total fraction after washing in toluene.

Table 2: Course Aggregate requirements
Source: Transport and Main Roads Specifications (PSTS108) Reclaimed Asphalt Pavement Material-2014

Table 7.1 – Coarse aggregate requirements

Coarse Aggregate Properties	Acceptance Criteria	Test Method
Particle size distribution	Contractor's nominated grading envelope	AS 1141.11.1
Materials finer than 75 µm	Report	AS 1141.12
Particle shape (for fraction retained on the 9.5 mm AS sieve for each constituent aggregate nominal size): using 2:1 caliper ratio using 3:1 caliper ratio	 ≤ 25% ≤ 10%	 AS 1141.14 AS 1141.14
Fractured face(s) for aggregates derived from gravels and meta-sediments: at least two fractured faces at least one fractured face	 ≥ 85% ≥ 100%	 RMS T239 RMS T239
Strength and durability: Wet strength Wet/dry strength variation Degradation factor	 ≥ 150 kN ≤ 35% ≥ 40%	 AS 1141.22 AS 1141.22 Q208B
Polished aggregate friction value (PAFV)	Wearing course ≥ 48 (unless otherwise specified in Clause 1 of Annexure PSTS108.1) All other courses ≥ 44	Q203
Water absorption	≤ 2.5%	AS 1141.6.1
Particle density (dry basis):	Report all	AS 1141.6.1

Table 3: Fine Aggregate requirements
Source: Transport and Main Roads Specifications (PSTS108) Reclaimed Asphalt Pavement Material-2014

Table 7.2 – Fine aggregate requirements

Fine Aggregate Properties	Acceptance Criteria	Test Method
Particle size distribution	Contractor's nominated grading envelope	AS 1141.11.1
Materials finer than 75 µm	Report	AS 1141.12
Water absorption[1]: Quartz sands All other types of aggregates	 ≤ 1.5% ≤ 3.0%	AS 1141.5
Aggregate soundness	≤ 12%	AS 1141.24
Particle density (dry basis)[1]:	Report	AS 1141.5

3.3.2. Process Control

Reclaimed asphalt pavement material must be blended, crushed and screened to ensure that:

a) 100% passes the 26.5 mm AS sieve

b) it is free flowing with consistent particle size distribution and complying with the tolerances specified in Table 7.3 of PSTS108 Aggregates for Asphalt and

c) it has minimal fracture of aggregate particles.

Table 4: Permissible variation to Aggregate requirements
Source: Transport and Main Roads Specifications (PSTS108) Reclaimed Asphalt Pavement Material-2014

Table 7.3 – Permissible variation to nominated particle size distribution of coarse and fine aggregates (% by mass of aggregate)

Description	Tolerance
Passing 26.5 mm and larger	± 10
Passing 4.75 mm to 19.0 mm	± 8
Passing 1.18 mm and 2.36 mm	± 6
Passing 0.300 mm and 0.600 mm	± 5
Passing 0.150 mm	± 3
Passing 0.075 mm	± 2

3.3.3. Stockpiling

At the processing site, separate stock piles shall be established for processed and unprocessed RAP material. Each processed stockpile must not exceed 1,000 tonnes.

3.3.4. Material conformance testing

Conformity of the RAP material with this Technical Specification shall be verified by sampling and testing, and providing records of process control.

3.3.4.1. Homogeneity

The Contractor's procedures, as detailed in their RAP management plan, must ensure the distribution of RAP aggregate in each stockpile is visually homogeneous and address the control of moisture in stockpiles.

3.3.4.2. Sampling

Sampling shall be undertaken in accordance with AS 1141.3.1 or Q060.

It grants up to 15% RAP to include into all dense graded mixtures. Asphalt mixtures from 15% to 30% are allowed to use in dense grade mixes. However it is not allowed for heavy duty wearing courses and modified polymer binders.

Austroads (2009, p. 18) stated that up to 20% RAP has very minimal impact on asphalt mixture, so there is no change required to modify the mix design. Austroads and AAPA both are recommending lowering the bitumen by one grade for 20% to 40% proportioning RAP to consider for aged binder. The Department of Transport and Main Roads Queensland (2010, p. 10) introduced very strict limits on using the RAP contents in asphalt. They suggested using 15% RAP contents in asphalt mix for dense graded non-surface layers with multi grade binders or traditional bitumen.

Table 5: Typical laboratory resilient values (Mpa)
Source: Austroads Pavement Design guide (2004).

Typical values of resilient modulus for dense graded asphalt are shown in Table A 23. Th
from Chapter 6 of the *Austroads Pavement Design Guide* (2004).

Table A 23: Typical laboratory resilient modulus values (MPa)

Binder Type	Mix size (Maximum particle size) (mm)					
	10		14		20	
	Range	Typical	Range	Typical	Range	Typical
Cl.170	2000-6000	3500	2500-4000	3700	2000-4500	3300
Cl.320	3000-6000	4500	2000-7000	5000	3000-7500	5200
Cl.600	3000-6000	6000	4000-9000	6500	4000-9500	7000
Multigrade	3300-5000	4500	3000-7000	5000	4000-7000	5500
SBS	1500-4000	2200	2000-4500	2500	3000-7000	3000
EVA			3000-6500	5600		

Note: Standard test conditions are 40 ms rise time and 25°C test temperature.

Chapter 4 Preliminary Materials Test

The chapter describes and discusses the materials involved in this research project. Six hot mix asphalt samples containing different proportions of RAP were prepared for the resilient modulus study. The characteristics of materials used in mix design preparation are described in detail.

4.1. Source of materials

The virgin aggregate and bitumen was supplied by University of Southern Queensland, and BORAL asphalt Toowoomba supplied the RAP material. The C600 and C320 grade bitumen were used in hot-mix preparations.

The aggregates used for the different mix design were 16 mm, 10 mm, 5/7 mm, crusher dust, fine sand and hydrated lime. The maximum size of 19.5 mm were sieved from RAP material.

4.1.1. Bitumen Characteristics

Most high performing roads in Australia are build and maintained using bitumen because it is durable and has exceptional waterproofing and adhesive properties. Bitumen used in road construction and maintenance are refined and blended to meet strict road engineering requirements and industry specifications.

Paving grade bitumen is categorized according to viscosity (degree of fluidity) grading. The higher the grade, the stiffer is the bitumen.

BP Bitumen Class 320

Class 320 bitumen is most commonly used to manufacture asphalt mixes. Due to its higher viscosity, stiffer asphalt mixes can be produced to improve resistance to shoving and other problems associated with higher temperature and traffic loads.

BP Bitumen Class 600

Class 600 bitumen is primarily used to manufacture extra heavy-duty asphalt pavements that need to endure substantial traffic loadings.

Table 6: Binder application of different classes (BP Bitumen)

Applications					
Bitumen	Sprayed	Asphalt			
		Light	Medium	Heavy	Extra
C170					
C240					
C320					
C450					
C600					

Table 7: Bitumen storage and handling temperature (BP Bitumen)

Storage & Handling Temperature Recommendations					
	C170	C240	C320	C450	C600
Storage for up to 30 days	135°C to 145°C				
Storage for up to 14 days	155°C to 165°C				
Storage for up to 7 days	170°C to 180°C				
Maximum temperature	190°C				
Minimum pumping temperature	135°C	140°C	145°C	150°C	155°C

Table 8: Recommended temperature for different classes (BP Bitumen)

Application Temperature Recommendations					
	C170	C240	C320	C450	C600
Asphalt mixing	150 - 160°C	155 - 165°C	155 - 165°C	160 - 170°C	165 - 175°C
Asphalt compaction	135 - 150°C	140 - 155°C	140 - 155°C	145 - 160°C	150 - 165°C
Sprayed sealing	175 - 185°C	180 - 190°C	180 - 190°C	N/A	N/A

Table 9: Typical characteristics of bitumen (BP Bitumen)

Property	Typical Value				
	C170	C240	C320	C450	C600
Viscosity at 60°C, Pa.s	170	240	320	450	600
Viscosity at 135°C, Pa.s	0.40	0.45	0.53	0.66	0.80
Viscosity at 60°C after RTFO, Pa.s	300	470	640	920	1300
Penetration at 25°C, dmm	70	58	46	36	27
Flashpoint, °C	360	360	360	360	360
Viscosity of residue at 60°C, % of original	180	190	200	205	215
Density at 15°C, kg/m³	1.04	1.04	1.04	1.04	1.04

4.1.2. Aggregate Characteristics

Characteristics of aggregate used in hot mix asphalt should meet some basic requirements.

The aggregates should strong, tough and durable.

The aggregates should have ability to be crushed into whole particles, without many thin, elongated and flaky particles.

The aggregates should have low permeability and low porosity.

Aggregate should be in correct gradation and particle size for asphalt pavement mixture.

Table 10: Grading limits for combined aggregate and filler
Source: Transport and Main Roads MRTS30-2015, pp.11

Table 10.3.1 – Grading limits for combined aggregate and filler

AS Sieve Size (mm)	Percentage Passing by Mass						
	Asphalt Nominal Size (mm)						
	OG10	OG14	DG7	DG10	DG14	DG20	DG28
37.5							100
26.5						100	90 – 100
19.0		100			100	90 – 100	76 – 90
13.2	100	90 – 100		100	90 – 100	72 – 86	64 – 80
9.50	90 – 100	50 – 70	100	90 – 100	68 – 82	60 – 76	55 – 71
6.70	50 – 70	28 – 42	90 – 100	66 – 80	–	–	–
4.75	28 – 42	16 – 26	68 – 82	46 – 62	42 – 58	41 – 58	40 – 56
2.36	9 – 17	8 – 14	44 – 58	28 – 42	28 – 42	28 – 42	28 – 42
1.18	7 – 13	6 – 11	29 – 41	19 – 31	19 – 31	19 – 31	19 – 31
0.600			22 – 32	13 – 23	13 – 23	13 – 23	13 – 23
0.300	4 – 8	3 – 7	12 – 20	9 – 17	9 – 17	9 – 17	9 – 17

Table 11: Maximum permitted variation for dense graded asphalt
Source: Queensland Transport and Main Roads Materials Testing Manual-2014, Q309

Table 3 - Maximum permitted variation for dense graded asphalt

Sieve size (mm)	Variation (% by mass)	Sieve size (mm)	Variation (% by mass)
≥ 9.50	± 7	0.600	± 4
6.70	± 6	0.300	± 3
4.75	± 6	0.150	± 2
2.36	± 5	0.075	± 1
1.18	± 4		
Binder content (%)		± 0.3*	

* May be tightened to achieve specification compliance

4.2. Aggregate Grading

Department of Transport and Main Roads (2013) recommended test method Q103B Particle Size Distribution of Aggregate (Dry Sieving) 1996. This test is applicable to filler material, course and fine aggregate and is based on dry sieving. This test based on AS 1141.11.1: Particle distribution-Sieving method. This test differs from Australian Standards because the method does not require the pre-coating agent to be removed before to sieving.

Figure 7: Sieves to be used in aggregate grading
Source: EO-MINERS<http://www.fhwa.dot.gov/engineering/geotech/pubs/05037/05a.cfm>

4.2.1. Test Equipment Required

The following apparatus are required

- Balance of suitable capacity, having a resolution and with a limit of performance as detailed in Table 1
- Sieves, 26.5 mm, 19.0 mm, 16.0 mm, 13.2 mm, 9.50 mm, 6.70 mm, 4.75 mm, 2.36 mm, 1.18 mm, 0.600 mm, 0.300 mm, 0.150 mm and 0.075 mm as required, complying with AS 1152.
- Mechanical sieve shaker (optional).
- Sieve brushes
- Drying oven of suitable capacity, having a temperature of 105-110°C and complying with AS 1289.0.
- Container, of suitable size for drying.

Figure 8: Automatic sieve analysis

4.2.2. Test Procedure

The procedure shall be as follows:

- Determine the nominal size of the aggregate by assessing the sieve size at which not more than 10 percent of the particles are larger. Prepare the sample according to test Method Q101 to obtain a test portion which, when dry, will comply with the minimum mass requirement of Table 12.

Table 12: Test portion and balance requirement

Source: Department of Transport and Main Road (2013) test method Q103B

Table 1 – Test portion and balance requirements

Aggregate nominal size (mm)	Minimum test portion mass (g)	Balance resolution (g)	Balance limit of performance range (g)
28	10000	10	± 50
20	5000	1	± 5
16	3000	1	± 5
14	2500	1	± 5
10	1000	1	± 5
7	600	0.1	± 0.5
5	500	0.1	± 0.5
Fine Aggregate	100	0.1	± 0.05
Filler	50	0.01	± 0.05

- Determine the mass of the container (m1).
- Place the test portion in the container and dry in the oven to constant mass. The material is considered to have reached a constant mass when the difference between successive weighings, after a further 1 hour drying at 105-110°C, is not more than 1 percent of the total of the previous moisture losses. For pre-coated aggregate, longer drying times may be necessary to remove all volatiles from the aggregate prior to testing.
- Determine the mass of the container and test portion (m2).
- Sieve the subsample by hand or with a mechanical shaker through the sieves appropriate to the aggregate nominal size, ensuring no sieve is overloaded.
- When sieving fine materials such as fillers, the underside of the sieves may be lightly brushed with a soft fine brush to prevent aggregation of particles (balling) and blinding of the apertures. With some materials such as hydrated lime, balling can only be overcome by lightly brushing

- At the end of sieving, hand sieve each portion retained until the mass passing each sieve in one minute is less than 1% of the mass of material retained on that sieve.
- Determine the mass of aggregate on each sieve (m_r).

4.2.3. Calculations

$$P_r = \frac{100M}{m2 - m1}$$

P_r = *cumulative percent retained on a particular sieve*

M = *cumulative mass retained on the paricular sieve* (g)

$m1$ = *mass of empty container* (g)

$m2$ = *mass of container and dry aggregate* (g)

4.3. RAP bitumen content and aggregate grading of asphalt

This test based on the principles of AS 2891.3.1: Bitumen content and aggregate- Reflux method. This test explains the procedure for determination of the bitumen content of asphalt by solvent extraction.

4.3.1. Test Equipment Required

- Balance of suitable capacity, with a resolution of at least 0.1 g and with a limit of performance within the range of 0.5 g. ±
- Centrifuge, an electric centrifuge capable of holding at least two 15 mL aliquots.
- Hotplate, capable of maintaining a temperature of 305ºC (Note 10.1).
- Fume cupboard.

- Flask, conical flask of 2 L capacity with a ground glass neck of at least 55 mm diameter and fitted with a stopper.
- Condenser, double surface condenser to fit the neck of the flask.
- Beaker, of at least 100 mL capacity.
- Containers, two flat-bottomed aluminum containers of approximate dimensions 100 mm diameter and 75 mm depth and equipped with tightly fitting slip-on lids.
- Metal tray, of sufficient capacity to contain the aggregate.
- Sieves, 37.5 mm, 26.5 mm, 19.0 mm, 13.2 mm, 9.50 mm, 6.70 mm, 4.75 mm, 2.36 mm, 1.18 mm, 0.600 mm, 0.300 mm, 0.150 mm, 0.075 mm and reinforced 0.075 mm as required complying with AS 1152.
- Sieve brush.
- Mechanical sieve shaker (optional).

4.3.2. Test Procedure

The following procedure shall be conducted on a single test portion for asphalt of nominal size less than 20 mm and on two test portions for asphalt of nominal size 20 mm or larger.

- Weigh the flask with stopper and record the mass to the nearest 0.1 g (1m).
- Obtain a representative sample of approximately 1200 g by coning and quartering in accordance with Subsection 4.2 of Test Method Q301.
- With the flask held at an angle of about 45 degrees, transfer the sample to the flask and allow it to cool. Weigh the flask with stopper and record the mass to the nearest 0.1 g (2m).
- Add a quantity of solvent to the flask at least equivalent in mass to the sample mass.

- Fit the reflux condenser to the flask and gently warm the flask and contents on the hotplate in the fume cupboard to dissolve the binder (Note 10.5). Shake the flask frequently during this refluxing operation to prevent binder from caking on the bottom of the flask.

Figure 9: RAP binder contents test

- Allow the flask to cool to room temperature with the condenser still in position. Remove the condenser and fit the stopper.
- Weigh the flask and stopper and record the mass to the nearest 0.1 g (3m).
- Perform the following procedure on two aliquots:
- Using the beaker, transfer an aliquot of at least 15 mL of the solution from the flask to the centrifuge tube(s). Stopper the tube(s) immediately and centrifuge to separate any suspended mineral matter.

- Weigh a container with lid and record the mass to the nearest 0.001 g (4m).
- Pour the supernatant liquid from the centrifuge tube(s) into the container, taking care not to disturb the settled mineral matter, and fit the lid. Weigh the container immediately and record the mass to the nearest 0.001 g (5m).
- Remove the lid and place the container on the hotplate maintained at a temperature of 305 ±10ºC in the fume cupboard to evaporate the solvent. Continue the heating for two minutes after fumes are first seen to rise from the binder (Note 10.1).
- Remove the container from the hotplate, replace the lid and allow the container to cool to room temperature.
- Weigh the container and lid and record the mass to the nearest 0.001 g (6m).

4.3.3. Calculations

$$B_a = \frac{(m_3 - m_2)(m_6 - m_4)100}{(m_5 - m_6)(m_2 - m_1)}$$

$B_a = \ binder\ content\ based\ on\ one\ aliquot(\%)$

$m_2 = mass\ of\ flask\ and\ stopper\ and\ asphalt\ sample\ (g)$

$m_6 = mass\ of\ container\ and\ lid\ and\ binder\ (g)$

$m_4 = \ mass\ of\ container\ and\ lid$

$m_5 = \ mass\ of\ container\ and\ lid\ and\ supematant\ liquid\ (g)$

$m_1 = mass\ of\ flask\ and\ stopper\ (g)$

Calculate the total mass of aggregate as follows:

$$m = \frac{m_s(100 - B)}{100}$$

$m = total\ mass\ of\ aggregate\ (g)$

$m_s = total\ mass\ of\ sample\ (g)$

$B\ = average\ binder\ content\ of\ sample(\%)$

Calculate the percentage of aggregate passing through each sieve as follows:

$$P_P\ = 100 - \frac{100M}{m}$$

$P_P\ = percentage\ of\ aggregate\ passing\ sieve(\%)$

$M\ = cumulative\ mass\ retained\ on\ sieve\ (g)$

Chapter-5 Experimental Methodology

This chapter describes the methods used to determine mix design parameters including aggregate grading, bitumen contents, temperature range, compaction level, percentage of air voids, the bulk specific gravity, of mix, including the particular results, and the principle investigations.

5.1. Hot Mix Design Preparation

The purpose of mix design is to prepare the combination of materials with such percentages that will maximize the engineering properties of asphalt pavement. Important factors are to increase the service life of product, safe and comfortable surface with reduced maintenance requirement in future. In mix design selection of bitumen type quantity, different aggregate size with different proportions, temperature, mixing time will optimize the required performance of asphalt pavement.

In this research an approved mix design procedure by Transport and Main Roads Specification MRTS30 dense grade-2015 has been selected. For this research 20 mm dense grade mix design has been selected which is in common use throughout the Queensland. Dense graded asphalt is general purpose asphalt which may be used for corrector and surfacing layers as well as structural layers. Dense Grade 20 and Dense Grade 28 mixes are intended to be used as structural layers. These mixes shall be relatively rut resistant when used with a binder, suitable for the traffic environment, and have an average permeability of not more than 15 μm/s when initially placed to minimize moisture damage to the layer and oxidation of the binder during service

Batches incorporated with 0%, 15%, 25%, 35%, 45% and 55% RAP prepared ,tested and compared against the results of 0% RAP like fully virgin materials sample. It is essential that the aggregate grading is uniform between each batch in order to make a meaningful comparison of results.

The grading limits for combined aggregate and filler materials should be according to specified limits for an adjacent sieve size.

After determine the density of aggregate nearly 4300 grams material sieved as per following table. This material should be enough to prepare three specimens.

Table 13: 0% RAP Mix design

Determination of Sieve Analysis					0% RAP
A.S Sieve Size	Cumulative Mass Retained M(g)	% Passing P = 100 - ((100 X M/T)	Virgin 85%	RAP %	Specification Limits
37.5 mm	0	100.0			
26.5 mm	0	100.0			100
19.0 mm	0	100.0			90-100
13.2 mm	641.0	85.0	641.0	0.0	72-86
9.5 mm	1112.4	74.0	1112.4	0.0	60-76
6.7 mm	1625.8	62.0	1625.8	0.0	40-70
4.75 mm	2010.9	53.0	2010.9	0.0	41-58
2.36 mm	2695.5	37.0	2695.5	0.0	28-42
1.18 mm	3166.0	26.0	3166.0	0.0	19-31
0.60 mm	3551.1	17.0	3551.1	0.0	13-23
0.30 mm	3765.1	12.0	3765.1	0.0	09--17
0.15 mm	3893.4	9.0	3893.4	0.0	08--19
0.075 mm	4021.7	6.0	4021.7	0.0	05--15
Total Mass of Test Sample(RAP+Virgin)		(T) (g)	4278.5		

Table 14: 15% RAP Mix design

Determination of Sieve Analysis					15% RAP
A.S Sieve Size	Cumulative Mass Retained M(g)	% Passing P = 100 - ((100 X M/T)	Virgin 85%	15% RAP	Specification Limits
37.5 mm	0	100.0			
26.5 mm	0	100.0			100
19.0 mm	0	100.0			90-100
13.2 mm	641.0	85.0	544.9	96.2	72-86
9.5 mm	1112.4	74.0	945.5	166.9	60-76
6.7 mm	1625.8	62.0	1382.0	243.9	40-70
4.75 mm	2010.9	53.0	1709.3	301.6	41-58
2.36 mm	2695.5	37.0	2291.1	404.3	28-42
1.18 mm	3166.0	26.0	2691.1	474.9	19-31
0.60 mm	3551.1	17.0	3018.4	532.7	13-23
0.30 mm	3765.1	12.0	3200.3	564.8	09--17
0.15 mm	3893.4	9.0	3309.4	584.0	08--19
0.075 mm	4021.7	6.0	3418.4	603.3	05--15
Total Mass of Test Sample(RAP+Virgin)		(T) (g)	4278.5		

Table 15: 30% RAP Mix design

Determination of Sieve Analysis					30% RAP
A.S Sieve Size	Cumulative Mass Retained M(g)	% Passing P = 100 - ((100 X M/T)	Virgin 70%	30% RAP	Specification Limits
37.5 mm	0	100.0			
26.5 mm	0	100.0			100
19.0 mm	0	100.0			90-100
13.2 mm	641.0	85.0	448.7	192.3	72-86
9.5 mm	1112.4	74.0	778.7	333.7	60-76
6.7 mm	1625.8	62.0	1138.1	487.7	40-70
4.75 mm	2010.9	53.0	1407.6	603.3	41-58
2.36 mm	2695.5	37.0	1886.8	808.6	28-42
1.18 mm	3166.0	26.0	2216.2	949.8	19-31
0.60 mm	3551.1	17.0	2485.8	1065.3	13-23
0.30 mm	3765.1	12.0	2635.6	1129.5	09--17
0.15 mm	3893.4	9.0	2725.4	1168.0	08--19
0.075 mm	4021.7	6.0	2815.2	1206.5	05--15
Total Mass of Test Sample(RAP+Virgin)		(T) (g)	4278.5		

Table 16: 40% RAP Mix design

Determination of Sieve Analysis					40% RAP
A.S Sieve Size	Cumulative Mass Retained M(g)	% Passing P = 100 - ((100 X M/T)	Virgin 60%	40% RAP	Specification Limits
37.5 mm	0	100.0			
26.5 mm	0	100.0			100
19.0 mm	0	100.0			90-100
13.2 mm	641.0	85.0	384.6	256.4	72-86
9.5 mm	1112.4	74.0	667.4	445.0	60-76
6.7 mm	1625.8	62.0	975.5	650.3	40-70
4.75 mm	2010.9	53.0	1206.5	804.4	41-58
2.36 mm	2695.5	37.0	1617.3	1078.2	28-42
1.18 mm	3166.0	26.0	1899.6	1266.4	19-31
0.60 mm	3551.1	17.0	2130.7	1420.4	13-23
0.30 mm	3765.1	12.0	2259.0	1506.0	09--17
0.15 mm	3893.4	9.0	2336.1	1557.4	08--19
0.075 mm	4021.7	6.0	2413.0	1608.7	05--15
Total Mass of Test Sample(RAP+Virgin)		(T) (g)	4278.5		

Table 17: 50% RAP Mix design

Determination of Sieve Analysis					50% RAP
A.S Sieve Size	Cumulative Mass Retained M(g)	% Passing P = 100 - ((100 X M/T)	Virgin 50%	50% RAP	Specification Limits
37.5 mm	0	100.0			
26.5 mm	0	100.0			100
19.0 mm	0	100.0			90-100
13.2 mm	641.0	85.0	320.5	320.5	72-86
9.5 mm	1112.4	74.0	556.2	556.2	60-76
6.7 mm	1625.8	62.0	812.9	812.9	40-70
4.75 mm	2010.9	53.0	1005.5	1005.5	41-58
2.36 mm	2695.5	37.0	1347.7	1347.7	28-42
1.18 mm	3166.0	26.0	1583.0	1583.0	19-31
0.60 mm	3551.1	17.0	1775.6	1775.6	13-23
0.30 mm	3765.1	12.0	1882.5	1882.5	09--17
0.15 mm	3893.4	9.0	1946.7	1946.7	08--19
0.075 mm	4021.7	6.0	2010.9	2010.9	05--15
Total Mass of Test Sample(RAP+Virgin)		(T) (g)	4278.5		

Table 18: 60% RAP Mix design

Determination of Sieve Analysis					60% RAP
A.S Sieve Size	Cumulative Mass Retained M(g)	% Passing P = 100 - ((100 X M/T)	Virgin 40%	60% RAP	Specification Limits
37.5 mm	0	100.0			
26.5 mm	0	100.0			100
19.0 mm	0	100.0			90-100
13.2 mm	641.0	85.0	256.4	384.6	72-86
9.5 mm	1112.4	74.0	445.0	667.4	60-76
6.7 mm	1625.8	62.0	650.3	975.5	40-70
4.75 mm	2010.9	53.0	804.4	1206.5	41-58
2.36 mm	2695.5	37.0	1078.2	1617.3	28-42
1.18 mm	3166.0	26.0	1266.4	1899.6	19-31
0.60 mm	3551.1	17.0	1420.4	2130.7	13-23
0.30 mm	3765.1	12.0	1506.0	2259.0	09--17
0.15 mm	3893.4	9.0	1557.4	2336.1	08--19
0.075 mm	4021.7	6.0	1608.7	2413.0	05--15
Total Mass of Test Sample(RAP+Virgin)		(T) (g)	4278.5		

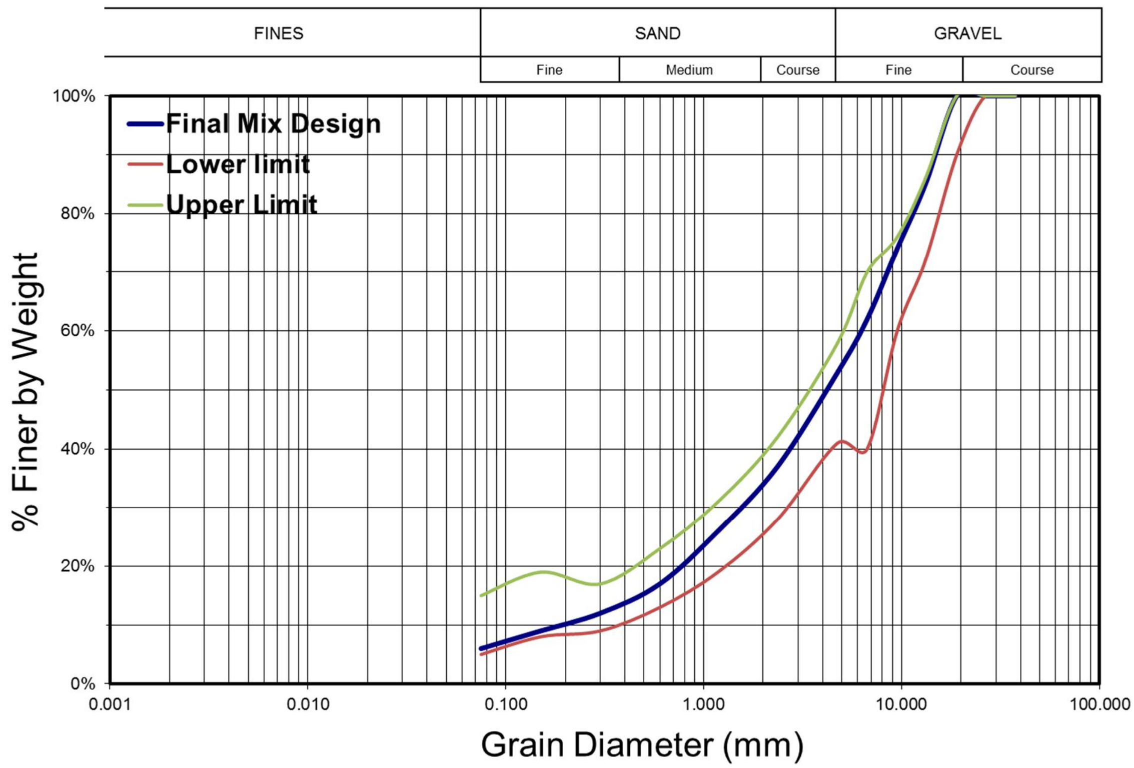

Figure 10: Sieve analysis for final Mix Design

5.1.1. Binder Contents

The bitumen content of mix design shall comply with Table 10.3.2 of technical specification of Transport and Main Road, MRTS30 dense graded and open graded asphalt Table 19.

Table 19: Asphalt mix design requirements for dense graded asphalt
Source: Queensland Transport and Main Roads MRTS30-2015

Table 10.3.2 – Asphalt mix design requirements

Property	Unit	Limit	Value						
			Asphalt Nominal Size (mm)						
			OG10	OG14	DG7	DG10	DG14	DG20	DG28
Effective binder volume	%	Minimum	9.0	8.0	–	10.0	9.5	9.0	8.5
Free binder volume	%	Minimum Maximum	6.5 –	5.5 –	– –	5.5 8.0	5.2 7.5	5.0 7.0	4.5 7.0
Fixed binder fraction	–	Minimum Maximum	– –	– –	0.25 0.60	0.30 0.60	0.30 0.60	0.30 0.60	0.30 0.60
Binder film thickness	µm	Minimum	15.0	15.0	–	–	–	–	
Air voids in the compacted mix (silicone sealed)	%	Minimum	13.0	13.0	–	–	–	–	–
Air voids in the compacted mix (mensuration)	%	Minimum	tbr	tbr	–	–	–	–	–
Abrasion loss	%	Maximum	30	30	–	–	–	–	–
Binder drainage	%	Maximum	0.3	0.3	–	–	–	–	–

5.1.2. Determining the Optimum Compaction Temperature

Determination of mixing and compaction temperature is an important factor in mix preparation. A certain level of viscosity must be maintained to ensure that the asphalt bitumen is properly fluid for mixing and compaction. Asphalt mix temperature maintained according to Department of Transport and Main Roads materials testing manual edition-4 2014.

Table 20: Temperatures for laboratory mix production of dense graded asphalt
Source: Queensland Transport and Main Roads Materials Testing Manual-2014

Table 4 - Temperatures for laboratory mix production

Component	Asphalt type	Temperature (°C)*	
		Component	Mixing bowl
Class 320 bitumen	Dense graded, stone mastic	160 - 170	210 - 230
Class 320 bitumen	Open gaded	160 - 170	180 - 190
Class 600 bitumen	Dense graded	160 - 170	210 - 230
Multigrade bitumen	Dense graded	160 - 170	210 - 230
A5S polymer modified binder	Dense graded, stone mastic	170 - 180	230 - 250
A5S polymer modified binder	Open graded	170 - 180	200 - 210
Reclaimed asphalt pavement	Dense graded	160 - 170	210 - 230

* For binders other than those listed, the appropriate temperatures may be interpolated/extrapolated based on binder viscosities

5.2. Hot mix Asphalt sample preparation

This method describes the procedure of specimen preparation according to Q-309, Department of Transport and Main Roads materials testing manual edition-4 2014.

5.2.1. Apparatus

The following apparatus is required:

- Mixer, a mechanical mixer comprising a mixing bowl of sufficient capacity to contain an asphalt mix, and an appropriate stirrer which will not cause excessive breakdown of the aggregates and filler. A Hobart dough mixer of 35 L capacity equipped with a heavy duty wire whip stirrer has been found suitable.
- Balance of suitable capacity, with a resolution of at least 1 g and with a limit of performance within the range of ± 5 g.
- Drying oven of suitable capacity, having a temperature of 105-110°C and complying with AS 1289.0.
- Oven of suitable capacity and capable of heating a sample of binder to a temperature of 160- 180ºC.
- Hotplate.
- Heating container, metal container able to be heated to the required temperature (see step 7.3) and of sufficient capacity to contain the aggregates and added filler.
- Heat source, for heating the aggregates and filler to about 220ºC where a bitumen binder is to be used, and to about 240ºC where a polymer modified binder is to be used, for example gas burner.
- Thermometer, a partial immersion thermometer or other suitable temperature measuring device having a temperature range of at least 150 - 250ºC and graduated to 1ºC or less with an uncertainty of no more than 0.5ºC.
- Quartering table, a heated metal tray of appropriate dimensions to contain an asphalt mix. A tray of dimensions 750 mm square has been found suitable.
- Mixing tools, assorted metal scoops, trowels and spatulas.
- Containers, metal or heavy duty plastic containers of sufficient capacity to contain the aggregate size fractions. Containers of length 420 mm, width 280 mm and height 150 mm have been found suitable.

- Sample dividers, riffles with slot widths of approximately 50 mm, 25 mm, 13 mm and 7 mm.
- Sieves, 37.5 mm, 26.5 mm, 19.0 mm, 13.2 mm, 9.50 mm, 6.70 mm, 4.75 mm, 2.36 mm,1.18 mm, 0.600 mm, 0.300 mm, 0.150 mm, 0.075 mm and reinforced 0.075 mm as required complying with AS 1152.
- Mechanical sieve shaker (optional).
- A means for washing the aggregate size fractions.

5.2.2. Preparation of aggregates and added filler

- Dry the aggregate and added fillers in oven
- Calculate the total quantity of aggregates and fillers required for mix design samples.
- For RAP incorporated samples, calculate the quantity of aggregates and filler in the RAP material.
- Sieve the material using the test method Q103B, and place each sieved size fraction into a separate labeled aggregate container.
- Wash the sieved materials until the wash water is clear, except the material passing0.075 mm.
- Dry the washed materials in drying oven.
- Record the design binder content of the mix.

5.2.3. Preparation of mix

The mixing bowl prepared as per following procedures.

- Empty the bowl and scrape adhering fines from the bowl.
- Preheat the mixing bowl in the oven or on hotplate.
- Weigh the required masses of each size fraction for a particular mix into the heating container.

Figure 11: Mixing the material in mixing bowl

- Heat the container and contents to the appropriate temperature (Table 4). During the heating process, mix the contents periodically using the scoop to provide an even temperature distribution.
- Heat sufficient binder (and RAP material where applicable) for the mix in the oven to the appropriate temperature (Table 4).
- Weigh the heated mixing bowl and record the mass (m1) to the nearest 1 g.
- Remove the container from the heat source and empty the contents carefully into the mixing bowl, ensuring that any fines adhering to the container are returned to the mix by brushing.

- With the contents of the mixing bowl at the appropriate temperature (Table 4), weigh the mixing bowl and contents and record the mass (m2) to the nearest 1 g.
- Heated aggregate, filler, and binder transferred to the preheated bowl in appropriate proportions.
- Mix the materials all together in a planetary style mixer
- Once the aggregate particles fully coated transfer the materials to a hotplate.
- Split the asphalt into equally quantity, mix the material thoroughly and then formed into a cone, ensuring proper distribution of coarse particles.
- Transferred the material into a mould, and kept in an oven at temperature according to (Table 4) for an hour.

5.3. Compaction Methods

The object of compaction is to reduce the air voids to achieve the friction between aggregate and bond between bitumen and aggregate. Harvey and Eriksen (1994) stated that different compaction method produce specimens with significantly different permanent deformation responses to repeated shear loading, which indicated each method of compaction gives a particular type of aggregate orientation and binder-aggregate film.

Austroads recommends specifically the Gyropac compactor method (AS2891.2.2), which uses a kneading effort to compact specimens, and Marshall Compaction hammer, which uses impact weight to compact specimens.

5.3.1. Gyropac Compactor

Gyropac compactor uses the process which simulates the roller action during compaction activity. Roberts et al. (1996) stated that it can vary the pressure, gyration angle, and the frequency of gyrations to simulate compaction process.

Figure 12: Gyropac Compactor (IPC global)

Table 21: Specification of Gyropac by IPC Global

Specification	**Description**
Gyration angle	0 - 3° with defined angles of 2° and 3° ± 0.1°
Gyratory speed	Fixed 60 cycles per minute
Specimen diameter	100 mm and 150 mm ± 0.1 mm
Compactive force	100 mm specimen 0 – 310 kPa
	150 mm specimen 0 – 700 kPa
Specimen height	65 mm and 85 mm for 100 and 150 mm samples respectively
Height indicator	Between 50 and 170 mm
Gyration counter	0 – 10,000 cycles

5.3.1.1. Test Equipment Required

- Gyratory Compactor
- Mould for sample preparation
- Oven
- Thermometer
- Steel Wearing discs
- Paper discs
- Balance
- Heat resistant boards
- Mixing equipment
- Mittens and tongs
- Specimen extractor
- Personal safety equipment

5.3.1.2. Test Procedure

A microwave oven can be used for the maintenance of compaction temperature in place of a conventional heating oven. For mixes produced in a laboratory environment the asphalt shall comply with the 'Conditioning' requirement of AS 2891.2.1 prior to compaction. Conditioning of commercially produced asphalt shall not apply.

The following procedure shall apply to obtain required compaction for every sample.

- Load the platen and base plate and preheat the mould to 150^{o}C
- Set gyratory angle 2 degrees, 240 kPa vertical loading stress and 120 cycles.
- Use brush to put little oil on paper discs so they do not stick with samples after compaction.
- Place the baseplate, lower wearing disc and paper disc into the mould.

- Put 2500 g of asphalt to the mould.
- Place a wearing disc, a circular paper disc, and upper loading platen on top of the asphalt, and then place the mould in the gyratory compactor.
- Start the compactor for the allowed set number of revolutions.
- Remove the sample from the mould by specimen extractor and let the sample to cool.

5.3.2. Asphalt Marshall Compactor

This method explains the process for preparation of specimens of asphalt mix. This method is used for asphalt mixes not exceeding 28 mm nominal size. Marshall Compactor or Marshall hammers automatically compact the specimen. The numbers of blows need to set and the mold needs to hold in position with a clamping device. The sliding hammer falls on the sample from a constant distance for each blow.

This compaction method is based on AS2894.5. It was carried out according to Main roads testing manual Q305.

Figure 13: Marshall Compactor

Table 22: Compaction equipment dimensions
Source: TMR Material Testing Manual (Q305) -2013

Compaction Equipment	Mix Nominal Size (mm)			
	≤20		>20	
	Dimension	Tolerance	Dimension	Tolerance
Compaction Mould				
Internal diameter of cylinder (mm)	101.6	± 0.2	150.0	± 0.2
Internal diameter of collar (mm)	101.6	± 0.2	150.0	± 0.2
Wall thickness (mm)	6	minimum	8	minimum
Compaction Hammer				
Mass of sliding weight (kg)	4.53	± 0.02	9.92	± 0.05
Free fall of sliding weight (mm)	457	± 1	460	± 3
Diameter of tamping face (mm)	98.5	± 0.1	149	± 0.2
Compaction Pedestal				
Wooden block, air dry density (kg/m^3)	720	± 50	720	± 50

Table 23: Mix Compaction Temperature
Source: TMR Material Testing Manual (Q305) -2013

Binder	Asphalt Type	Compaction Temperature (°C)
Class 170 Bitumen	Dense Graded	142 ± 3
Class 170 Bitumen	Open Graded	120 ± 3
Class 320 Bitumen	Dense Graded, Stone Mastic	150 ± 3
Class 320 Bitumen	Open Graded	125 ± 3
Class 600 Bitumen	Dense Graded	155 ± 3
M1000/320 Multigrade Bitumen	Dense Graded	155 ± 3
Polymer Modified Binder	Dense Graded, Stone Mastic	160 ± 3
Polymer Modified Binder	Open Graded	140 ± 3

5.3.2.1. Apparatus

The following apparatus required as per Queensland testing manual 2013, Q305. The tolerance for this method is mentioned in above table 20 and 21.

- Automatic Marshall Compactor
- Specimen mould, having an internal diameter of 101 mm and a height of 89 mm. The wall thickness should not less than 6 mm and mould base thickness 18mm with an extension collar of internal diameter of 101.6 mm, height of 70 mm and wall thickness of 6 mm.
- The Marshall compactor with a flat round tamping face of diameter 98.5 mm and sliding weight with a mass of 4.53 kg. The free fall of weight should not less than 457 mm.
- A hydraulic jack for specimen extraction from mould, fitted with a plate on ram. The plate shall be of 100 mm diameter and 6 mm thick for 101.6 mm diameter of test specimen.
- Breaking Head shall be consisting of upper and lower cylindrical segments mounted on a base with guide bushes.
- Marshall Compactor shall drive at constant speed to perform a rate of travel 51mm/min with the capability of at least 22 kN force application.
- Oven, for heating the mould and hammer plate.
- A Balance of suitable capacity to measure the mass of sample.
- Temperature gauge to record the mixture temperature.
- Measuring device to measure the height of specimen.
- Marker
- A Steel tray, steel trowel, spatulas and scoop.
- Paper segments, suitable grease lubricant for lubricating the moulds.

5.3.2.2. Test Procedure

The following procedure shall be performed to make each epecimen.

- Heat the oven to required compaction temperature.
- Assemble and place the compaction mould in oven for 1 hour.
- Heat up the hammer face on hotplate to required temperature.
- Calculate the required mass of mixture to fill the moulds to obtain the specimen height 63.5 mm.
- Prepare the asphalt mixture.
- Take out the compaction mould from oven, place the paper segment on the mould base.
- Put back the mould into oven for 60 +/- 5 minutes.
- Take out the mould from the oven, record the required temperature, place the paper segment on top of the mould.
- Transfer the compaction mould in Marshall Compactor and compact the mixture with 50 blows from each side with hammer rate of 60 to 70 blows per minute.
- Remove the test specimen from the machine and remove the collar and base plate mark the identity on sample clearly.
- Extrude the test specimen from the mould once it cooled in air.

5.4. Determination of Compacted density

We have to conduct the compacted density test according to the Queensland Department of Transport and Main Road (Q306B Department of Transport and Main Road 2015). This test will determine the bulk density of compacted asphalt samples to calculate the void ratio. This test based of the principles of AS2891.9.2.

5.4.1. Test Procedure

The following procedure will be carried out for each compacted specimen:

- Weigh the sample and record its mass to the nearest 0.1 g.
- Immerse the sample in the water container for 5 minutes.
- Attach the suspension device to the balance and tare the balance.
- Transfer the sample to the suspension device, removing any adhering air bubbles to the surface and record its mass to the nearest 0.1 g. Record the water temperature to the nearest 1°C.
- Remove the sample from the container and blot the surface dry with a damp towel.
- Weigh the saturated sample and record the mass to the nearest 0.1 g.

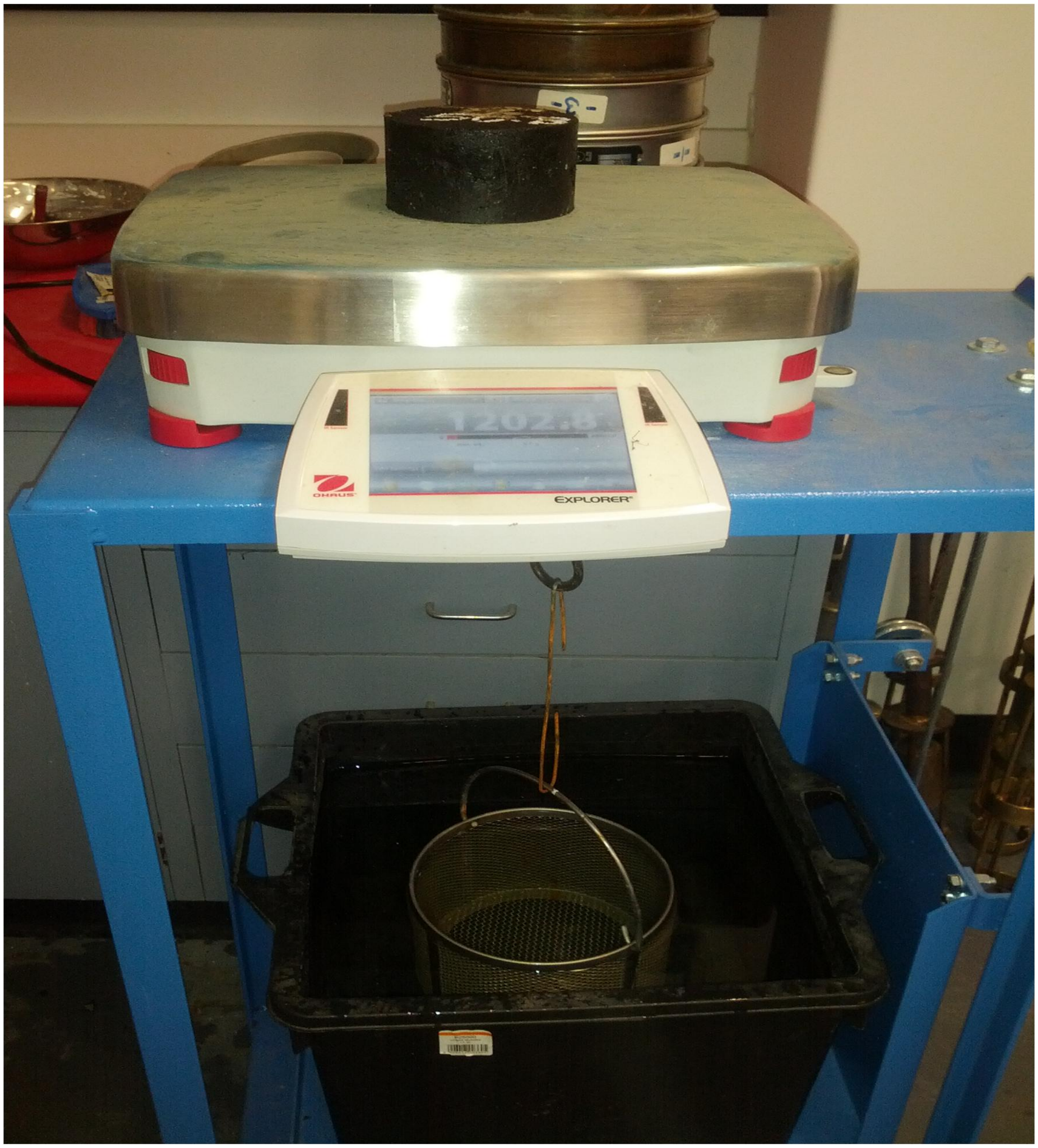

Figure 14: Compacted density test for specimens

This test method is applicable only to asphalt having water absorption no more than 2.0% when calculated as follows:

$$WA = \frac{100(m_3 - m_1)}{m_1}$$

where,

$WA = water\ absorption\ of\ the\ asphalt(\%)$

$m_1 = mass\ in\ air\ of\ the\ sample(g)$

$m_3 = mass\ in\ air\ of\ the\ saturated\ sample(g)$

5.5. Determination of the Maximum Specific Gravity/Maximum Density

This test has been conducting according to Queensland Department of Transport and Main Road test method (Q307A Department of Transport and Main Road 2015). The purpose of this test is to determine the maximum voids less density of Asphalt using water displacement. We required the maximum density value to calculate the void ratio.

5.5.1. Apparatus

The following apparatus is required:

- Drying oven of suitable capacity, having a temperature of 105-110ºC and complying with AS 1289.0.
- Vacuum flask, a thick-walled annealed glass flask of at least 2 L capacity. It shall be fitted with a stopper containing provision for a vacuum tube and metal stirrer.
- Vacuum system, comprising a vacuum tube connected to a vacuum pump or water aspirator capable of producing an absolute pressure of about 8 kPa in the stoppered flask. The system shall include a vacuum measuring device and, where a vacuum pump is used, a suitable water trap (Note 9.1).
- Balance of suitable capacity, with a resolution of at least 0.1 g and with a limit of performance within the range of ± 0.5 g. The balance shall be fitted with an attachment for below balance weighing.
- Attachment, a non-absorbent device to suspend the vacuum flask from the balance while the flask is fully immersed in the container.
- Container fitted with an overflow and filled with clean water to the overflow. The container shall be of suitable dimensions to allow the vacuum flask to be completely immersed without contacting any part of the container.

- Thermometer, a partial or total immersion thermometer or other suitable temperature measuring device having a temperature range which includes the test temperature, and graduated to 1ºC or less with an uncertainty of no more than 0.5ºC.
- Metal stirrer, of suitable design to allow manual agitation of the test portion in the flask while under vacuum.

5.5.2. Test Procedure

- The following procedure will be carried out on two test portions per mix design (Naumann 2013):
- Weigh the flask and record its mass to the nearest 0.1 g.
- Fill the container to over flow, fit the attachment and tare the balance.
- Immerse the flask in the container and suspend it from the balance with the attachment.
- Record the mass of the flask in water to the nearest 0.1 g and the water temperature.
- Remove the flask from the water and dry the outside surface.
- Place the flask on the balance and tare the balance.
- Transfer the test portion of asphalt to the flask.
- Weigh the flask with the asphalt sample and record the mass of sample to the nearest 0.1 g.
- Fill the flask with water, covering the asphalt with about 50 mm of water. Add a drop of detergent to the flask.
- Fit the stopper with metal stirrer and vacuum tube to the flask.

- Evacuate the flask to a gauge pressure of about -93 kPa. Maintain the vacuum for 15 minutes and frequently agitate the sample with the stirrer to assist trapped air bubbles to escape.
- Remove the stopper, stirrer and vacuum tube.
- Carefully immerse the flask in the container, ensuring the sample remains covered with water and no air is reintroduced to the sample.
- Tare the balance and attach the immersed flask.
- Record the mass of the flask and sample in water to the nearest 0.1 g and the water temperature to the nearest 1°C.

5.5.3. Calculations

Maximum density of each test portion calculated as follows:

$$D_m = \frac{m_3 - m_1}{\left(\frac{m_3 - m_4}{D_{W2}}\right) - \left(\frac{m_1 - m_2}{D_{W1}}\right)}$$

$where,$ $D_m = maximum\ density\ of\ the\ test\ portion \left(\frac{t}{m^3}\right)$

$m_3 = mass\ of\ flask\ and\ test\ portion (g)$

$m_1 = mass\ of\ flask (g)$

$m_4 = mass\ of\ flask\ and\ test\ portion\ in\ water (g)$

$m_2 = mass\ of\ flask\ in\ water (g)$

$D_{W2} = density\ of\ water\ at\ temperature\ t2 \left(\frac{t}{m^3}\right)$

$D_{W1} = density\ of\ water\ at\ temperature\ t1 \left(\frac{t}{m^3}\right)$

Table 24: Density of water

Source: Transport and Main Roads Materials Testing Manual-2014

Table 2 – Density of water

Temperature (ºC)	Density (t/m³)	Temperature (ºC)	Density (t/m³)	Temperature (ºC)	Density (t/m³)
0	0.9998	14	0.9992	28	0.9962
1	0.9999	15	0.9991	29	0.9959
2	0.9999	16	0.9989	30	0.9957
3	1.0000	17	0.9988	31	0.9953
4	1.0000	18	0.9986	32	0.9950
5	1.0000	19	0.9984	33	0.9947
6	0.9999	20	0.9982	34	0.9944
7	0.9999	21	0.9980	35	0.9940
8	0.9999	22	0.9978	36	0.9937
9	0.9998	23	0.9975	37	0.9933
10	0.9997	24	0.9973	38	0.9930
11	0.9996	25	0.9970	39	0.9926
12	0.9995	26	0.9968	40	0.9922
13	0.9994	27	0.9965		

5.6. Determination of Air Voids Percentage

Air voids determination by the test method Q311 (void properties for compacted asphalt). This method based on AS/NZS 2891.8 voids and volumetric properties of compacted asphalt mix.

This test describes the method of calculation of voids ratio for a sample of compacted asphalt. In order to calculate voids it requires prior determination of the compacted density, maximum density, and binder content of the sample.

5.6.1. Calculations

Percentage by volume of air voids calculated as per following equation:

$$AV = 100\left(1 - \frac{D_C}{D_M}\right)$$

$where,\quad AV = air\ voids(\%)$

$$D_C = compacted\ density\ of\ sample\ \left(\frac{t}{m^3}\right)$$

$$D_M = maximum\ density\ of\ sample\ \left(\frac{t}{m^3}\right)$$

Determination of volume of Effective Binder

Volume of effective binder in the sample calculated as follows:

$$V_B = \frac{D_C}{D_B}\left(B - b_a + \frac{Bb_a}{100}\right)$$

$where,\quad V_B = effective\ binder\ volume\ (\%)$

$$D_C = compacted\ density\ of\ sample\ \left(\frac{t}{m^3}\right)$$

$$D_B = density\ of\ the\ binder\ \left(\frac{t}{m^3}\right)$$

$$B = binder\ content\ of\ the\ sample\ (\%)$$

$$b_a = binder\ absorption\ of\ the\ aggregate(\%\ by\ mass\ of\ aggregate)$$

Determination of volume of voids in aggregate

Volume of voids in the mineral aggregate in the sample calculated according to Q311 as follows:

$$VMA = AV + V_B$$

$where\quad VMA = voids\ in\ the\ mineral\ aggregate(\%)$

$$AV = air\ voids(\%)$$

$$V_B = effective\ binder\ volume(\%)$$

Determination of volume of voids filled with Binder

Volume of voids filled with binder in the sample calculated according to Q311 as follows:

$$VFB = \frac{100V_B}{VMA}$$

where $VMA = voids\ in\ the\ mineral\ aggregate(\%)$

$VFB = voids\ filled\ with\ binder(\%)$

$V_B = effective\ binder\ volume(\%)$

5.7. Resilient Modulus Tensile Test

Resilient modulus can be tested on both field cores or laboratory prepared samples, results for both types of samples should match (Katicha 2003). Resilient modulus is determined using the triaxial test. The test applies a repeated axial cyclic stress of fixed magnitude, load duration and cycle duration to a cylindrical test specimen. While the specimen is subjected to this dynamic cyclic stress, it is also subjected to a static confining stress provided by a triaxial pressure chamber. It is essentially a cyclic version of a triaxial compression test; the cyclic load application is thought to more accurately simulate actual traffic loading (Pavement Interactive 2007).

Repeated Load Triaxial Test method is based on Australian Standards (AS 2891.13.1) and Queensland Test Method Q305. Preconditioning load pulses will be applied by computer software to find out the required maximum load which can obtain a specific range of strain. The computer system will automatically calculate the results. The modulus is very sensitive to rate of loading because of viscoelastic nature of asphalt.

Neumann (2013) stated that the rise time and load repetition period must be kept within 5 ms and 50 ms respectively. The recovered horizontal deformation used to calculate the difference between the peak horizontal deformation for a load pulse and the horizontal deformation at the end of rest time for the load pulse.

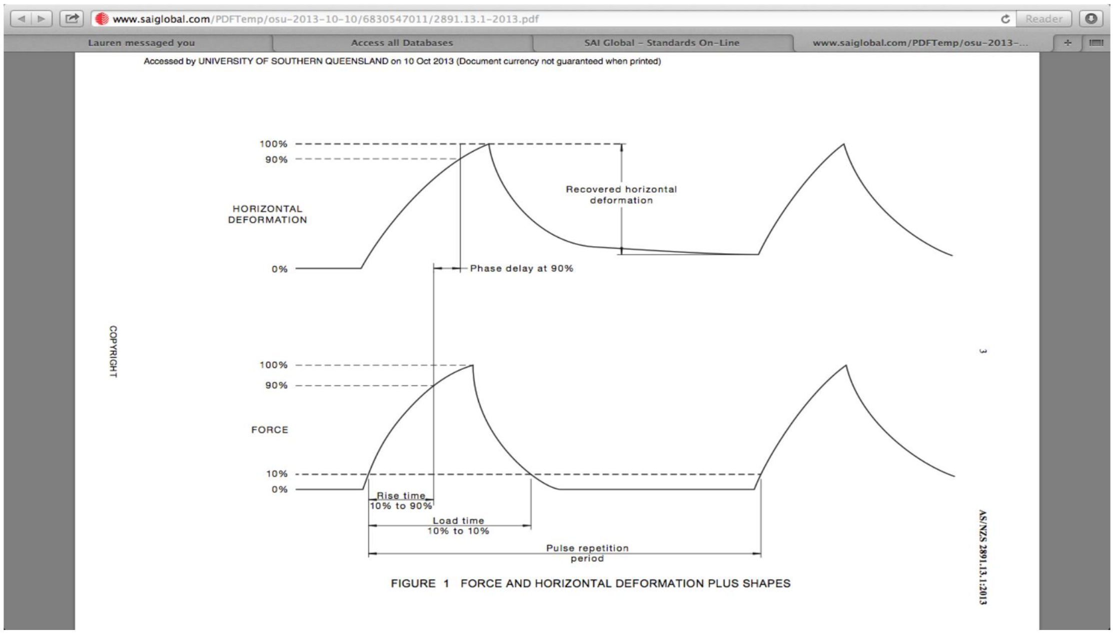

Figure 15: Force and horizontal deformation pulse shapes

Figure 16: MATTA Testing Machine for Resilient Modulus Test

5.7.1. Test Equipment Required

- MATTA testing machine
- Temperature cabinet
- Measuring and recording apparatus
- Plano-cylindrical-concave steel loading blocks
- Vernier caliper
- Digital thermometer
- Torque screwdriver

5.7.2. Test Procedure

- The following procedure will be carried out according to AS2891.13.1 on samples from each mix design:
- Mark two diameter lines at right angles to each other on one end of the test specimen.
- Measure the diameter nearest 0.1mm at both marked ends. Then take average of these measured diameters (D).
- Measure the height of the samples to the nearest 0.1 mm at the points where the diameters marked. Similar ways calculate the average of these measured heights (h_c).
- Place the samples in the temperature controlled cabinet set at 25°C until the samples temperature reach to equilibrium. Approximately 2 hours of time would be sufficient for this process.
- Input the specimen dimensions and estimated resilient modulus of the test sample into the computer test program.

- Place the sample centrally on the lower loading block where the diameter markings should orient vertically and horizontally.
- Fix the displacement measuring apparatus over the test specimen. Must need to ensure the transducers are in contact with a smooth, sound part of the curved surface of the test specimen. A slight adjustment to the seating of the specimen may be necessary to achieve this. The transducers must also be sitting centrally and diametrically opposite. Once the jig will correctly set, anchor it to the test sample by tightening the anchoring screws with a torque of 250 mN.m on each.
- Place the top loading black centrally on the test specimen.
- Adjust the transducers to ensure they are in the centre of their travelling range and lower the frame holder.
- Place the apparatus under the loading head and lower the load actuator ram onto the top of the loading block.
- Apply conditioning load pulses to allow the computer to determine the peak load required to ensure the recovered horizontal strain is within the specified limits for the test.
- Readjust the transducers to ensure they are in the centre of their travelling range.
- Run the resilient modulus test. The computer will automatically apply 5 load pulses and record the necessary measurements to calculate the resilient modulus.

  Calculations

Chapter 6 Results and Discussion

6.1. Bitumen Contents Results

Two samples of RAP material were tested to determine the bitumen contents. The results and an average of both samples are shown in the figure below. The bitumen contents of the first sample were found to be 4.37% and 2.525% respectively and similarly the bitumen contents for the second sample were 3.93% and 2.816%. Hence, the average of all four tests results was 3.41%.

Previous studies confirm this is a typical value. This value is recoverable from RAP material. Therefore, the 3.41% bitumen was used in mix design procedure to determine the quantity of recoverable binder and subsequently the amount of virgin binder to be accounted during adding the bitumen into the asphalt mixture.

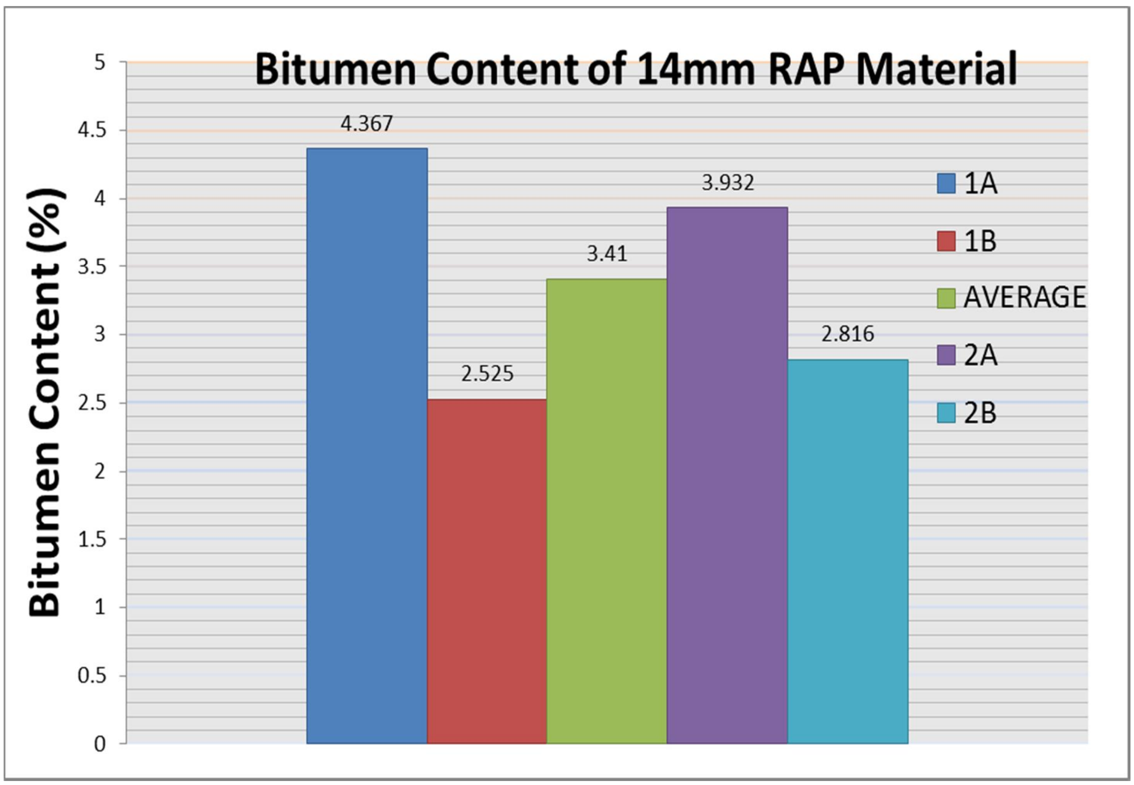

Figure 17: Binder contents of 14mm RAP material

The determination of binder contents of RAP is important for many reasons like specification acceptance and quality control. The binder contents effects the performance of mixture in stiffness, durability, strength, fatigue life, raveling, rutting and moisture damage areas. The excess of asphalt binder or the lower quantity of binder can cause the above stated problems.

6.2. Maximum Density Results

The maximum density or specific gravity of asphalt mixture is the specific gravity excluding air voids. Maximum density is a critical characteristic of hot mix asphalt as this value is used to calculate the air voids in compacted asphalt specimens.

Prior to compaction of the sample, each mix was tested for specific gravity. The results are shown in figure below. The trend of results was as expected where the value decreases gradually. According to results, virgin material is denser than RAP. Austroads 2012, states that higher density increases the resilient modulus. However, the present experimental result does not comply with it as resilient modulus increased with lower density.

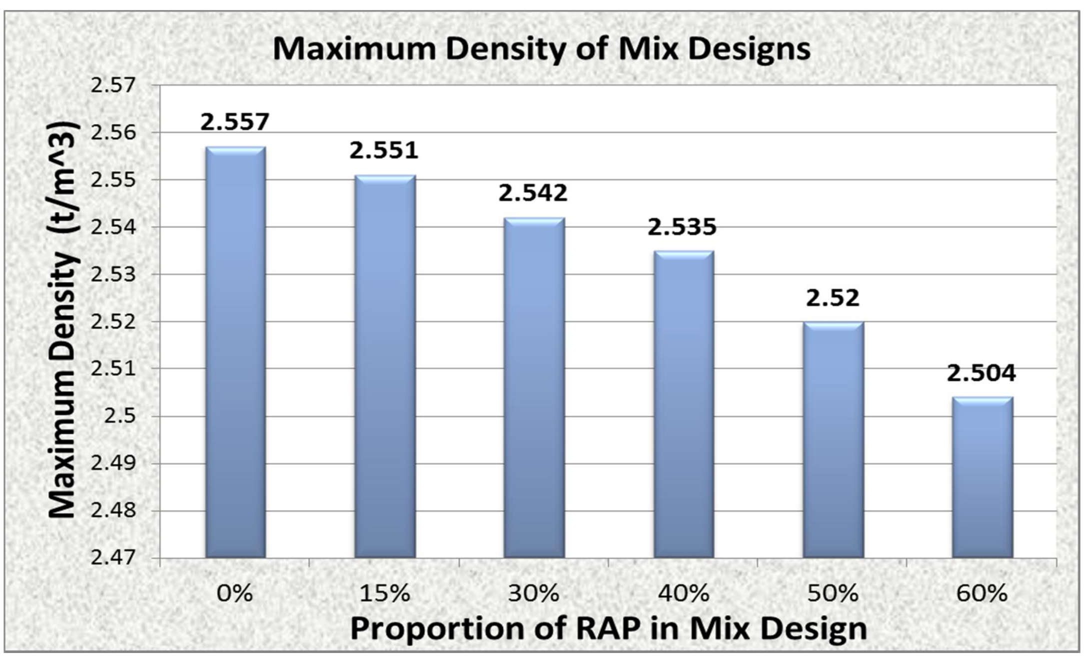

Figure 18: Maximum density of mix designs

6.3. Compacted Density Results

The compacted density test results are shown in figure below. The results shows the variations between the each sample, even the variation can be noted within same sample. Many factors have direct effects on density like temperature, mix properties and binder properties. Gradation of sample also can affect the compaction of individual specimen. The air voids of a specimen are inverse proportion to compacted density. As the density is less, the air voids are more. Therefore, it is important to do an adjustment in resilient modulus value for air voids presence in specimens.

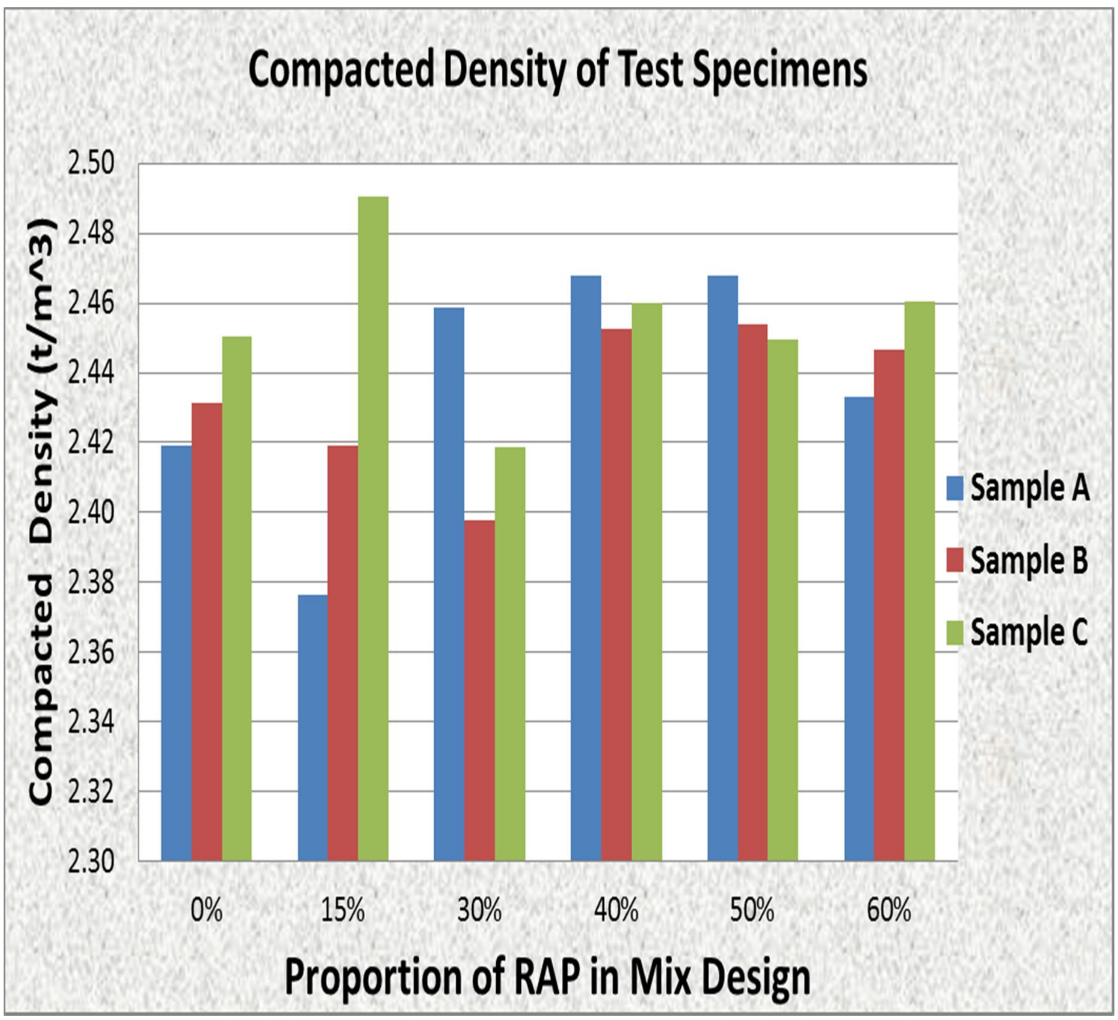

Figure 19: Compacted density of test specimens

Table 25: Compacted density for test specimens

RAP Proportion	A	B	C	Average
0%	2.42	2.43	2.45	2.43
15%	2.38	2.42	2.49	2.43
30%	2.46	2.40	2.42	2.43
40%	2.47	2.45	2.46	2.46
50%	2.47	2.45	2.45	2.46
60%	2.43	2.45	2.46	2.45

6.4. Air Voids Results

The figure below shows the results of air voids in each sample. The air voids for 0%, 15% and 30% are 4.8%, 4.8% and 4.6% respectively. There is significant drop in air voids when RAP proportion has increased to higher value. The drop in air voids for increased RAP contents may because of RAP material itself as RAP material was quite fine. As more fine and filler material is in mix, therefore less air voids noted in results.

The air voids in asphalt pavement are important as it have a profound effect on long-term pavement performance. An approximate "rule of thumb" is for every 1 percent increase in air voids will decrease about 350Mpa in resilient modulus of pavement. Therefore, higher air voids content tends to reduce the resilient modulus.

Table 26: Air Voids % of Specimens

RAP Proportion %	A	B	C	Ave
0%	5.4	4.9	4.2	4.8
15%	6.8	5.1	2.3	4.8
30%	3.3	5.7	4.9	4.6
40%	2.6	3.2	2.9	2.9
50%	2.1	2.7	2.8	2.5
60%	2.9	2.3	1.8	2.3

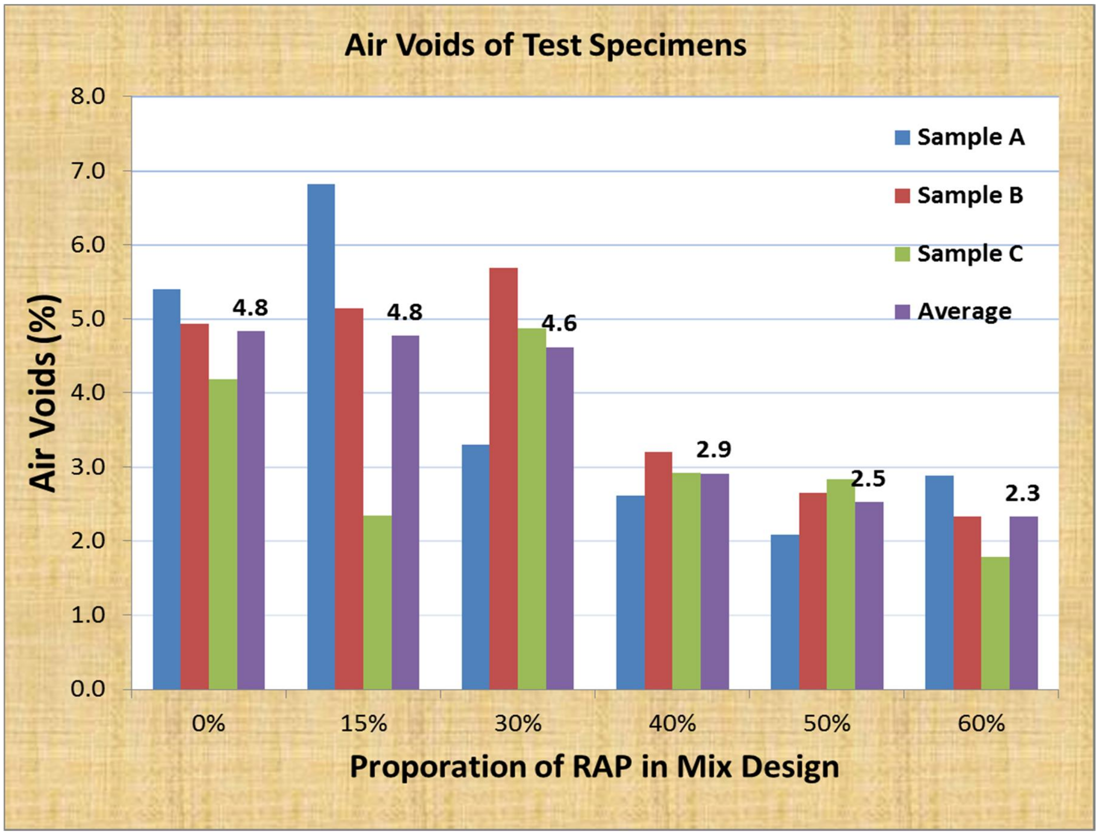

Figure 20: Air Voids of test specimens

6.5. Resilient Modulus Results

The figure below shows the results for the average resilient modulus of each mix design. The values shown in figure below are actual results for physical tests but without accounting the air voids effect; the comparison cannot be made at this stage as the air voids for every tested specimen is different. The air voids will affect the results of resilient modulus.

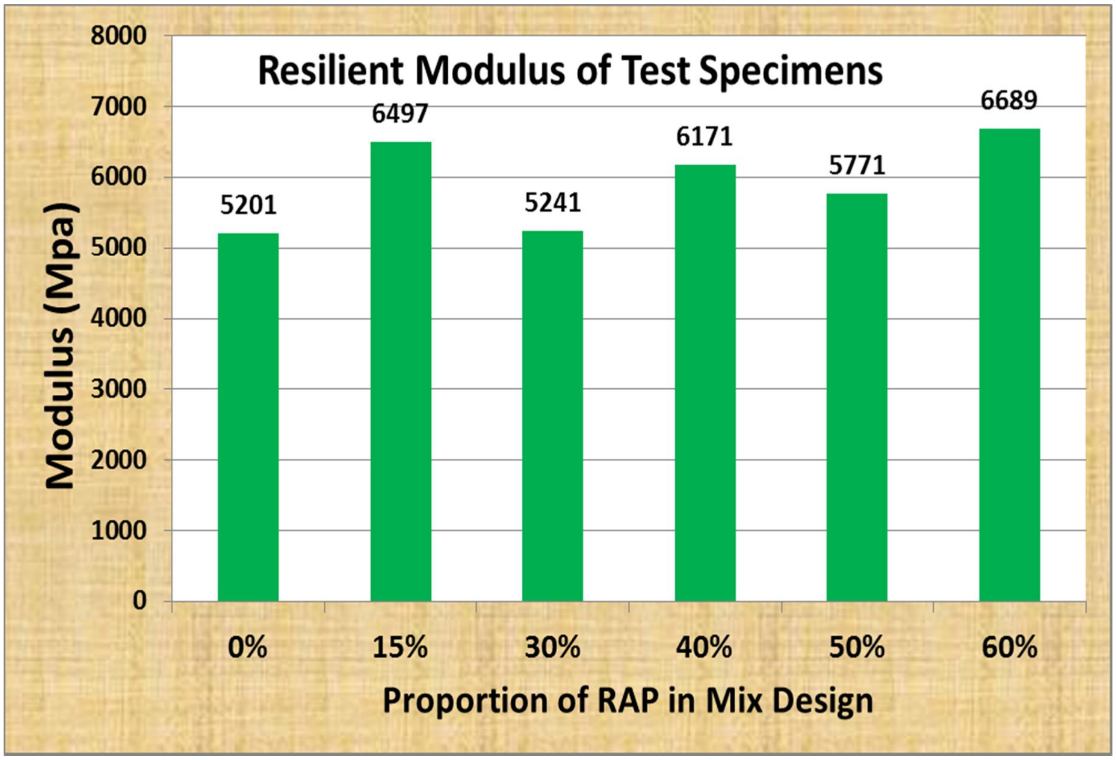

Figure 21: Resilient Modulus of test specimens

6.6. Adjusted Resilient Modulus

The figure below shows the comparison between the actual resilient modulus and adjusted resilient modulus for air voids. It has noted that the result shows the same trend in resilient modulus but lower than its actual value after adjustment made for air voids. The resilient modulus for virgin material with C600 binder shows the lowest modulus which is as expected but for the added fifteen percent RAP proportion the results are completely different than expectation. The increment in resilient modulus for 15% added RAP is 37%, which is opposing the current practice of adding the RAP in virgin asphalt. A small increment was expected, as the one lower grade binder and small amount of RAP used in this mix. This is a concern on the current Austroads recommended practice, which states that effects of adding 15% RAP in hot mix asphalt is negligible.

As C320 binder was used to compensate for aged binder of RAP material. Therefore 30% mix is softer or equal to controlled mix but 40, 50 and 60% added RAP mix design has higher modulus which lead to stiffer pavement.

Softer mix may reduce the fatigue cracking but on the other hand, it can lead to susceptibility of rutting. To prevent the rutting , an increased thickness would be required for the pavement layer.

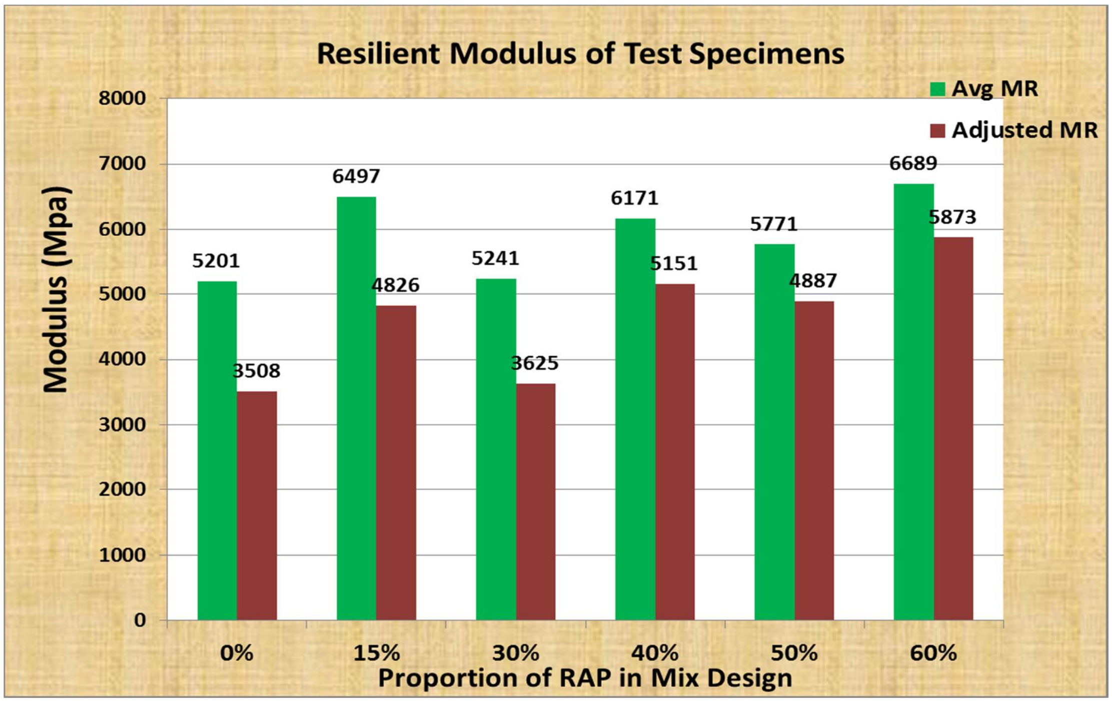

Figure 22: Adjusted Resilient Modulus

Table 27: Actual and Adjusted Resilient Modulus of test specimens

RAP Proportion	A	B	C	Avg M_R (Mpa)	Adjusted M_R (Mpa)
0%	5108	5529	4965	5201	3508
15%	6988	6420	6082	6497	4826
30%	4715	4751	6256	5241	3625
40%	6661	4730	7121	6171	5151
50%	5216	5930	6168	5771	4887
60%	6739	6528	6800	6689	5873

6.7. Effects on Mix Volumetric Properties

It is very important to understand the basic relationship between weight and volume of the hot mix asphalt. In the above results of specimens, it is important to review the air voids, volume of effective binder.

6.7.1. Mix Volumetric

Volumetric properties of hot mix asphalt are as important as resilient modulus to estimate the fatigue life of asphalt pavement. The result of volumetric calculations for each RAP percentage is presented below in table.

Table 28: Volumetric Properties of samples

RAP Proportion %	0%	15%	30%	40%	50%	60%
Bitumen Content %	4.7	4.7	4.7	4.7	4.7	4.7
Max Density (t/m^3)	2.557	2.551	2.542	2.535	2.52	2.504
Compacted Density (t/m^3)	2.43	2.43	2.43	2.46	2.46	2.45
Bitumen Density	1.04	1.04	1.04	1.04	1.04	1.04
Binder Absorption	0.4	0.4	0.4	0.4	0.4	0.4
VB	10.11	10.09	10.07	10.22	10.20	10.16
Air Voids %	4.8	4.8	4.6	2.9	2.5	2.3
VMA	14.94	14.86	14.69	13.13	12.73	12.49
VFB	67.6	67.88	68.56	77.81	80.16	81.33

In above shown results the volumetric results are very similar for 0%, 15% and 30% RAP proportioned mixtures. These results do not tend to have any major effect on resilient modulus of asphalt. However, the results for 40%, 50% and 60% are quite different from the results of virgin material's results. The reason for this variation could be incomplete bitumen blending with new binder. The RAP was preheated in the oven for two hours prior to mix with the virgin materials, if the RAP was not heated enough then the RAP binder does not properly mix with new binder. As RAP particles are in course gradation than the RAP aggregate, so if the RAP particles will not break down and mix thoroughly with virgin materials then with same compaction level a variation in VMA results expected.

The results of air voids also have an important factor in above results. Air voids in 0%, 15% and 30% are quite normal to typical value of 5% air voids. However, the air voids in 40%, 50% and 60% are lower than the normal value. Therefore, it is believed that the extra air voids in mix will protect it to become too much dense. If the in-situ air void becomes very low (less than 3%), the mix may eventually flow and caused the permanent deformation.

6.7.2. Fatigue Life

The fatigue life of pavement is its ability to withstand repeated loading without fracture.

Based on the above results of air voids and binder contents, it is noted that binder contents increased and air voids decreased for the specimens of 40%, 50% and 60% RAP proportions, which will result in increased fatigue life. Higher binder contents tends to an increased thickness of binder film between an increased RAP proportion and aggregate particles over a cross section in the direction of tensile stress. Tensile strength must be transmitted through binder, therefore more binder mean more bitumen area in cross section, so as a result less stress in asphalt.

The combination of an increased binder contents and decreased air voids % creates a kind of material which has thick binder films between aggregate particles transmitting tensile stress throughout the solid. The stress concentration will reduce due to air voids and at where the aggregate particle will in direct contact.

Chapter 7 Conclusions and Recommendations

7.1. Summary and Conclusion

Based on the results of this research, the RAP is a high quality and valuable material, which can reduce the use of virgin aggregate and binder and make hot mix asphalt more economical.

There is great potential of RAP usage in Australia and the wider use of recycled asphalt will generate economic and environmental benefits. However, widespread use of an increased proportion of RAP in asphalt mixtures requires support from road transport departments. Lack of information and guidance is a concern in this area. The current specifications and guidelines are not sufficient to make the most effective use of RAP material in asphalt pavements. There is a need to provide guidance and documented information about long term performance of RAP proportioned mix designs.

As discussed earlier common challenges for high proportioned RAP are specifications limits, lack of processing and RAP availability. In terms of performance, the most common issue is the quality of blending between virgin binder and RAP binder as well as the stiffening of the pavement, which results in surface cracking. The results uncovered here add further validation to findings in previous studies as outlined in the literature review: asphalt material displayed increasing stiffness with increasing amounts of RAP. However, the small quantity of RAP such as 15% also caused a significant increase in the resilient modulus, which ultimately reduces the pavement fatigue life. This shows the inadequacy of current specifications, which states that the impacts of small proportioned RAP are negligible.

Based on the results of this research, the soft grade binder is effective in reducing the resilient modulus and improving the fatigue life of asphalt pavement. It was noticed that up to 40% RAP proportioned mixture could have similar performance to virgin mixtures. However, careful consideration should be given to selection of mix design and binder grade. There is potential to overcompensate in the design of the mixes, which would result in inadequate stiffness (impacts on rutting). Therefore, one possibility is to provide a thicker layer to avoid rutting and protect the subgrade layers.

To avoid this situation and to increase the usage of RAP the following recommendations are provided:

- RAP obtaining, processing and stockpiling should be in accordance with standard techniques thus avoiding moisture and maintaining a proper grade.
- Random sampling and testing should be performed to identify the variability of RAP material properties.
- Plant production practices should regularly monitor to provide correct control of moisture content and scalping screens. The best quality of increased proportioned RAP asphalt can only be achieved with best practices. As a result, cost, energy and emission reductions will be realized.
- For high proportioned RAP, careful consideration should be given in the selection of binder grade to avoid rutting or stiffness.
- For each mix design that has a high percentage of RAP, a performance evaluation test should be performed. Many tests are available for evaluation of expected deformation, fatigue, and thermal cracking performance of pavements.
- Further guidelines and specifications are required for production, construction and long-term performance of RAP materials.
- Further work needs to be done in order to improve the use of RAP without compensating the pavement quality.

7.2. Achievement of Objectives

The primary objectives of the project have been achieved and described below:

- Based on background information and previous research, up to 15% RAP contents do not have any noticeable impacts on pavement performance. The current guidelines for RAP in Australia recommends up to 15% RAP addition in new dense grades asphalt mixtures without accounting for any binder ageing. However, for further increased RAP mixtures up to 30%, one grade lower binder is recommended as the highest percentage of RAP can cause stiffness and a higher resilient modulus.

- Current guidelines and relevant test methods have been reviewed prior to commencement of preparation of mix design. The mix design was prepared in accordance with standard procedures in an effort to compare the results obtained.

- All the relevant tests were carried out in USQ laboratory according to relevant test methods and standards. Each specimen was tested for resilient modulus in MATTA. Adjustment in the results was made to compensate for air voids.

- An analysis was carried out according to the current specification for reclaimed asphalt pavement. Findings of the results, suggests that these guidelines are not sufficient in reclaimed asphalt applications on a widespread basis in Australia.

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Appendix A – Project Specification

A1- Project Specification

University of Southern Queensland

SCHOOL OF CIVIL ENGINEERING AND SURVEYING

ENG4111/ENG4112 Research Project

PROJECT SPECEFICATION

FOR: ATHAR ASGHAR

TOPIC: EVALUATION OF STRENGTH CHARACTERISTICS OF RECYCLED BITUMINOUS PAVEMENT MATERIALS

SUPERVISOR: Dr. Soma Somasundaraswaran

PROJECT AIM: The aim of this research project is to evaluate the strength characteristics of asphalt samples containing different proportions of recycled asphalt compared with pure mix designs for the verification of current AUSTROADS specification for hot-in-place recycled asphalt pavement.

PROGRAMME: 15 March 2015

1. Background research about previously done experimental work for recycled asphalt mechanical properties (Resilient Modulus).
2. Review current AUSTROADS specification/standards in use for recycled asphalt pavement.
3. Review and establish test methods for resilient modulus.
4. Review mix design procedures and prepare samples containing various amount of recycled material.
5. Define the test procedure and conduct laboratory tests to find out resilient modulus of various mix design.
6. Report, analyse the data and compare the results with current AUSTROADS specification.
7. Report the outcomes and if time permits, investigate methods for further improvement in recycled asphalt performance.

AGREED:

Student:
Athar Asghar

Date: 05-03-2015

Supervisor:
Dr. Soma Somasundaraswaran

Date: 05/3/2015

Appendix B – Raw Materials test sheet

B1- 14mm RAP Test 1

ASPHALT TEST WORKSHEET - QDMR - SOLVENT

Date:	25-08-2015
Student:	Athar Asghar
Job No.	USQ Project
Mix Type:	14mm RAP

Determination of Bitumen Content (Test Method Q308A)		
Flask No.	2	
Mass Flask + Mix +Solvent (g) M3	3805	
Mass Flask + Mix (g) M2	2562	
Mass Flask (g) M1	1376	
Mass Solvent (g) S = M3 - M2	1243	
Mass Mix (g) M = M2 - M1	1186	
Tin No.	A	B
Mass Tin + Solvent (g) M5	130	127
Mass Tin + Bitumen (g) M6	110.8	110.4
Mass Tin (g) M4	110	110
Mass Sol in Tin (g) M9 = M5 - M6	19.2	16.6
Mass Bit. In Tin (g) M10 = M6 - M4	0.8	0.4
Mass Bit. In Samp. B = (M10 x S)/M9	51.792	29.952
%Bit by Mass (%) = (B X 100)/M	4.367	2.525
Ave Bit Content (%)	3.45	
Bit Limits		

Grading (Test Method Q308A)			
Grading Sieve (A.S.)	Accum Mass RET (g) C	% PASS (A - C)/A x 100	Spec Limits
26.5 mm	0	100	
19.0 mm	0	100	
13.2 mm	3	100	
9.5 mm	140	88	
6.7 mm	345	71	
4.75 mm	525	56	
2.36 mm	845	29	
1.18 mm	925	22	
0.60 mm	970	18	
0.30 mm	1015	14	
0.15 mm	1056	11	
0.075 mm	1096	8	
Total Mass Aggregate (g) A = M - ((b1+b2)/2)			1186

Tested by (Name): ____________________

Checked by (Name): ____________________

B2- 14mm RAP Test 2

ASPHALT TEST WORKSHEET - QDMR - SOLVENT	
Date:	25-08-2015
Student:	Athar Asghar
Job No.	USQ Project
Mix Type:	14mm RAP

Determination of Bitumen Content (Test Method Q308A)		
Flask No.	1	
Mass Flask + Mix +Solvent (g) M3	3810	
Mass Flask + Mix (g) M2	2570	
Mass Flask (g) M1	1380	
Mass Solvent (g) S = M3 - M2	1240	
Mass Mix (g) M = M2 - M1	1190	
Tin No.	A	B
Mass Tin + Solvent (g) M5	132	129
Mass Tin + Bitumen (g) M6	110.8	110.5
Mass Tin (g) M4	110	110
Mass Sol in Tin (g) M9 = M5 - M6	21.2	18.5
Mass Bit. In Tin (g) M10 = M6 - M4	0.8	0.5
Mass Bit. In Samp. B = (M10 x S)/M9	46.792	33.514
%Bit by Mass (%) = (B X 100)/M	3.932	2.816
Ave Bit Content (%)	3.37	
Bit Limits		

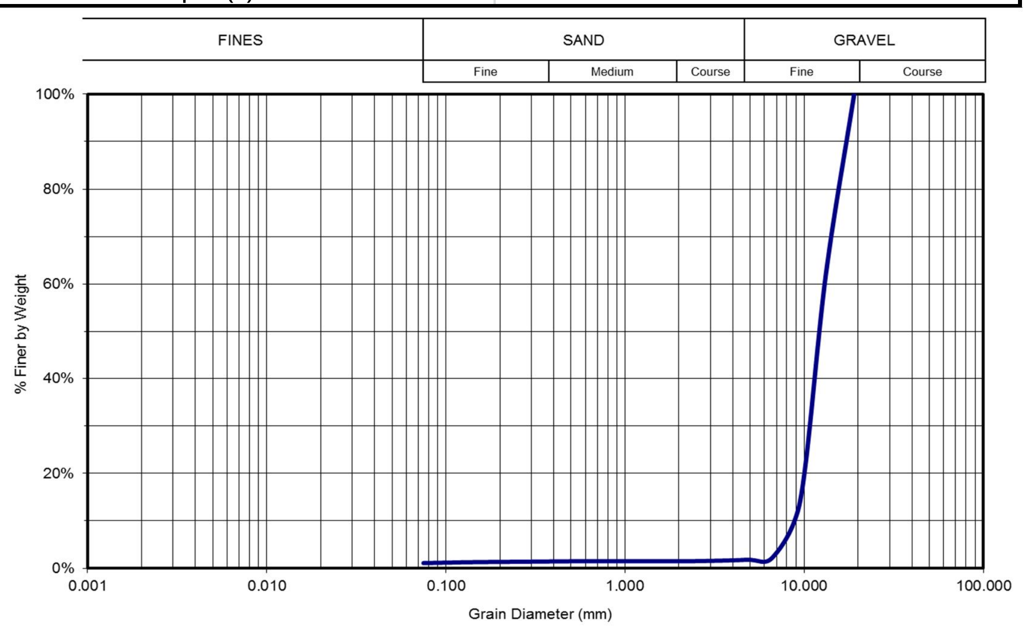
Grading (Test Method Q308A)			
Grading Sieve (A.S.)	Accum Mass RET (g) C	% PASS (A - C)/A x 100	Spec Limits
26.5 mm	0	100	
19.0 mm	0	100	
13.2 mm	5	100	
9.5 mm	145	88	
6.7 mm	342	71	
4.75 mm	574	52	
2.36 mm	855	28	
1.18 mm	930	22	
0.60 mm	965	19	
0.30 mm	1010	15	
0.15 mm	1067	10	
0.075 mm	1093	8	
Total Mass Aggregate (g) A = M - ((b1+b2)/2)			1190

Tested by (Name): ________________

Checked by (Name): ________________

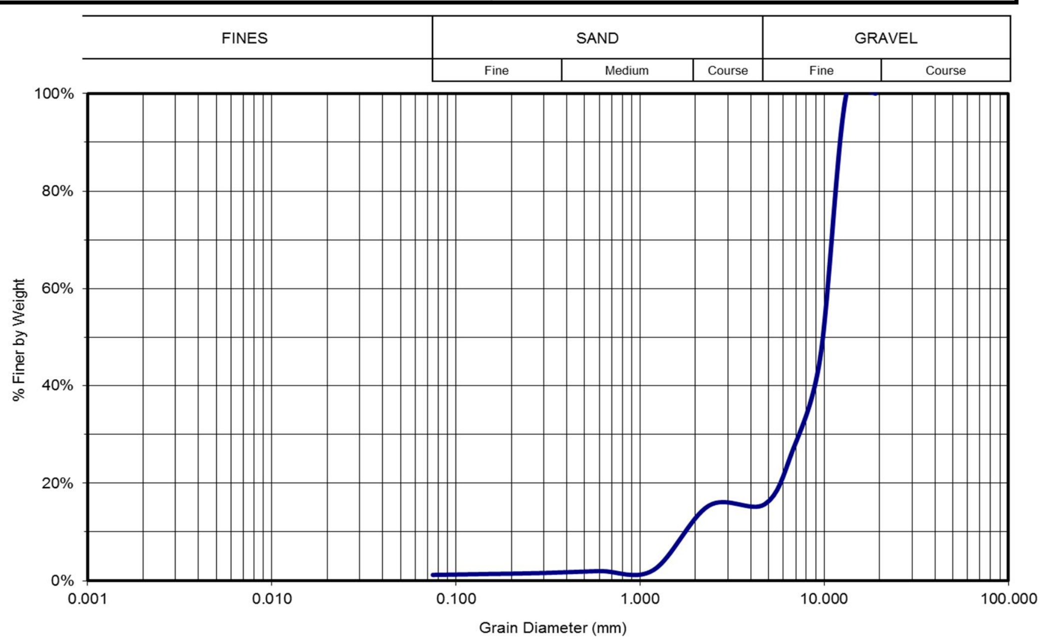
B3.16 mm Aggregate Grading

AGGREGATE GRADING WORKSHEET - QDMR			
Date:	25-07-2015		
Student:	Athar Asghar		
Job No.	USQ Project		
Mix Type:	16 mm		
Tray Number		16mm	
Final Mass Tray + Dry Sample	M(g)	1747.2	
Mass of Dry Sample	M(g)	1051.7	
Oven Test Temperature		110 C	
Determination of Sieve Analysis			
A.S Sieve Size	Cumulative Mass Retained M(g)	% Passing P = 100 - ((100 X M/T)	Specification Limits
37.5 mm	0	100.0	
26.5 mm	0	100.0	
19.0 mm	0	100.0	
13.2 mm	397.5	62.2	
9.5 mm	901.2	14.3	
6.7 mm	1026	2.4	
4.75 mm	1033	1.8	
2.36 mm	1036	1.5	
1.18 mm	1036	1.5	
0.60 mm	1036	1.5	
0.30 mm	1037	1.4	
0.15 mm	1038	1.3	
0.075 mm	1040	1.1	
Mass of Test Sample (T)		1051.7	



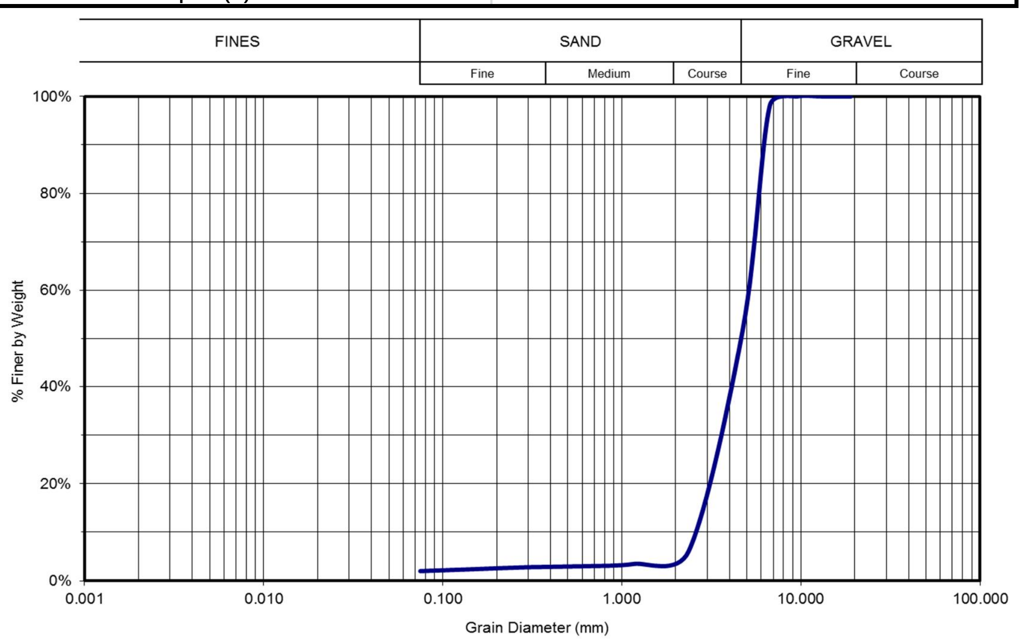
B4.10 mm Aggregate Grading

AGGREGATE GRADING WORKSHEET - QDMR			
Date:	25-07-2015		
Student:	Athar Asghar		
Job No.	USQ Project		
Mix Type:	10 mm		
Tray Number		10mm	
Final Mass Tray + Dry Sample M(g)		1925	
Mass of Dry Sample M(g)		1225	
Oven Test Temperature		110 C	
Determination of Sieve Analysis			
A.S Sieve Size	Cumulative Mass Retained M(g)	% Passing P = 100 - ((100 X M/T)	Specification Limits
37.5 mm	0	100.0	
26.5 mm	0	100.0	
19.0 mm	0	100.0	
13.2 mm	0	100.0	
9.5 mm	665	45.7	
6.7 mm	900	26.5	
4.75 mm	1033	15.7	
2.36 mm	1036	15.4	
1.18 mm	1198	2.2	
0.60 mm	1201	2.0	
0.30 mm	1205	1.6	
0.15 mm	1208	1.4	
0.075 mm	1210	1.2	
Mass of Test Sample (T)		1225	



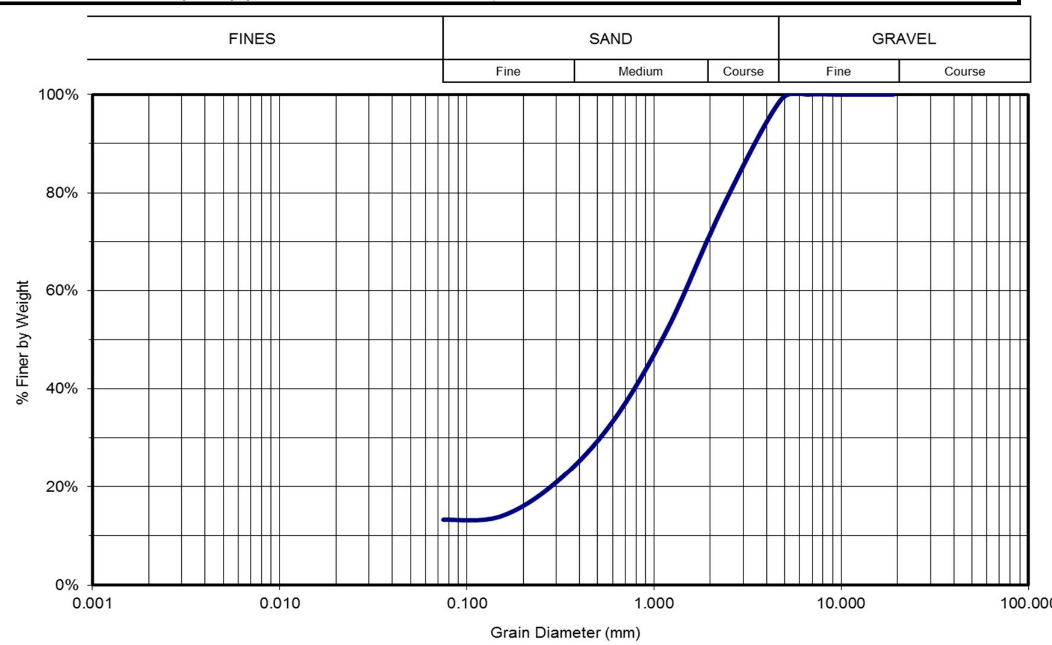
B5.5/7 mm Aggregate Grading

AGGREGATE GRADING WORKSHEET - QDMR			
Date:	25-07-2015		
Student:	Athar Asghar		
Job No.	USQ Project		
Mix Type:	5/7 mm		
Tray Number		5/7 mm	
Final Mass Tray + Dry Sample	M(g)	1850	
Mass of Dry Sample	M(g)	1150	
Oven Test Temperature		110 C	
Determination of Sieve Analysis			
A.S Sieve Size	Cumulative Mass Retained M(g)	% Passing P = 100 - ((100 X M/T)	Specification Limits
37.5 mm	0	100.0	
26.5 mm	0	100.0	
19.0 mm	0	100.0	
13.2 mm	0	100.0	
9.5 mm	0	100.0	
6.7 mm	21.7	98.1	
4.75 mm	550	52.2	
2.36 mm	1080	6.1	
1.18 mm	1110	3.5	
0.60 mm	1115	3.0	
0.30 mm	1118	2.8	
0.15 mm	1122	2.4	
0.075 mm	1127	2.0	
Mass of Test Sample (T)		1150	



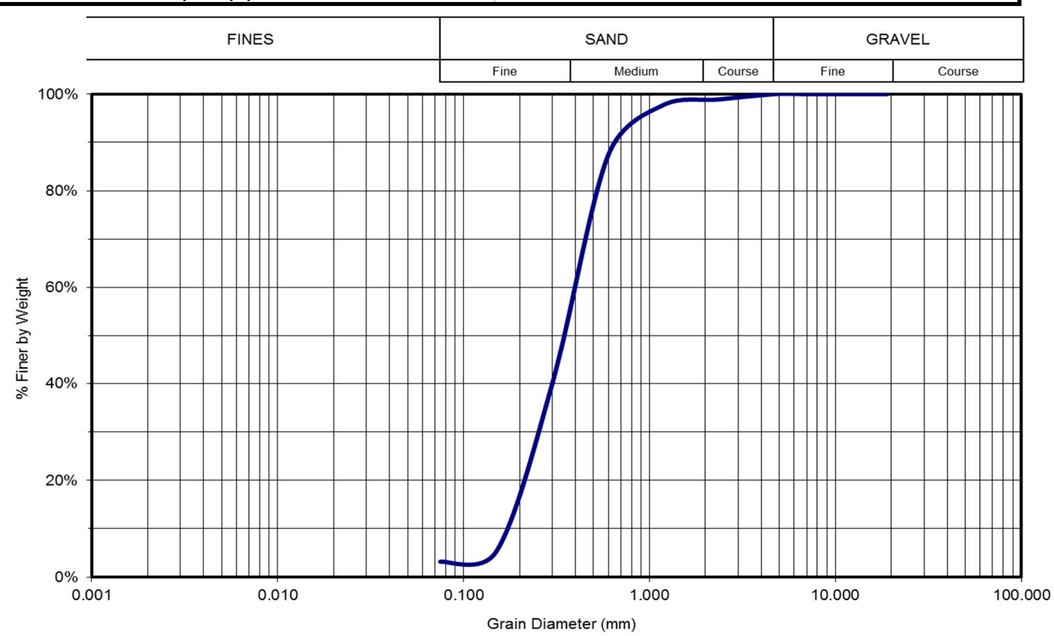
B6. Crusher Dust Grading

AGGREGATE GRADING WORKSHEET - QDMR			
Date:	25-07-2015		
Student:	Athar Asghar		
Job No.	USQ Project		
Mix Type:	Crusher Dust		
Tray Number		Crusher Dust	
Final Mass Tray + Dry Sample	M(g)	1600	
Mass of Dry Sample	M(g)	900	
Oven Test Temperature		110 C	
Determination of Sieve Analysis			
A.S Sieve Size	Cumulative Mass Retained M(g)	% Passing P = 100 - ((100 X M/T)	Specification Limits
37.5 mm	0	100.0	
26.5 mm	0	100.0	
19.0 mm	0	100.0	
13.2 mm	0	100.0	
9.5 mm	0	100.0	
6.7 mm	0	100.0	
4.75 mm	10	98.9	
2.36 mm	202	77.6	
1.18 mm	430	52.2	
0.60 mm	600	33.3	
0.30 mm	712	20.9	
0.15 mm	775	13.9	
0.075 mm	780	13.3	
Mass of Test Sample (T)		900	



B7. Fine Sand Grading

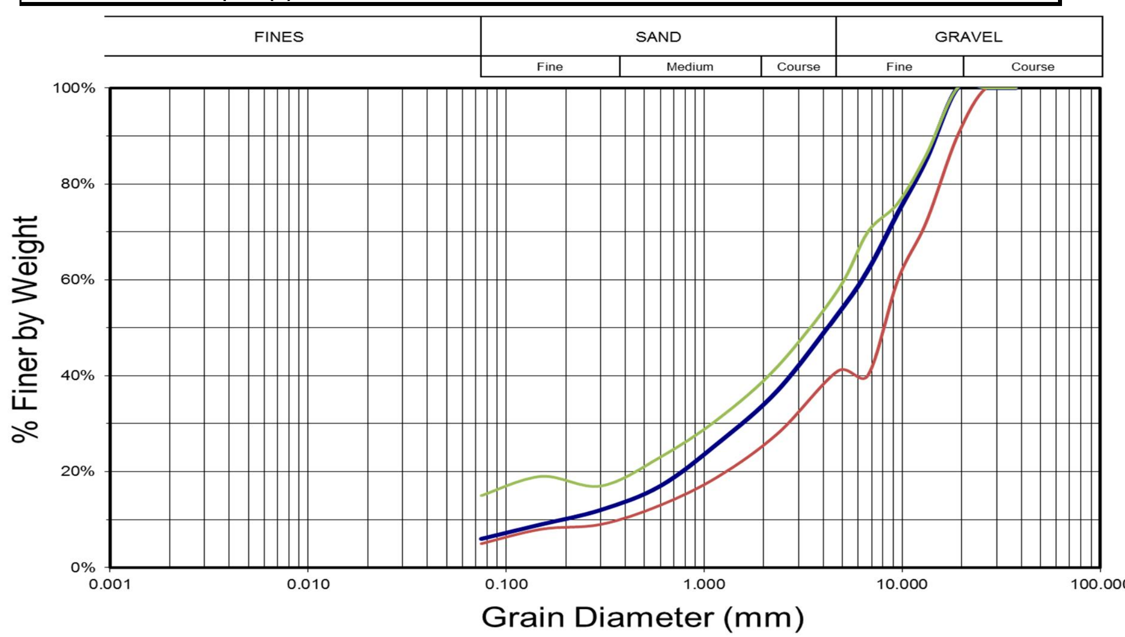
AGGREGATE GRADING WORKSHEET - QDMR			
Date:	25-07-2015		
Student:	Athar Asghar		
Job No.	USQ Project		
Mix Type:	Fine Sand		
Tray Number		Fine Sand	
Final Mass Tray + Dry Sample M(g)		1650	
Mass of Dry Sample M(g)		950	
Oven Test Temperature		110 C	
Determination of Sieve Analysis			
A.S Sieve Size	Cumulative Mass Retained M(g)	% Passing P = 100 - ((100 X M/T)	Specification Limits
37.5 mm	0	100.0	
26.5 mm	0	100.0	
19.0 mm	0	100.0	
13.2 mm	0	100.0	
9.5 mm	0	100.0	
6.7 mm	0	100.0	
4.75 mm	0	100.0	
2.36 mm	10	98.9	
1.18 mm	22	97.7	
0.60 mm	120	87.4	
0.30 mm	570	40.0	
0.15 mm	900	5.3	
0.075 mm	920	3.2	
Mass of Test Sample (T)		950	



Appendix C – Mix Design Calculation

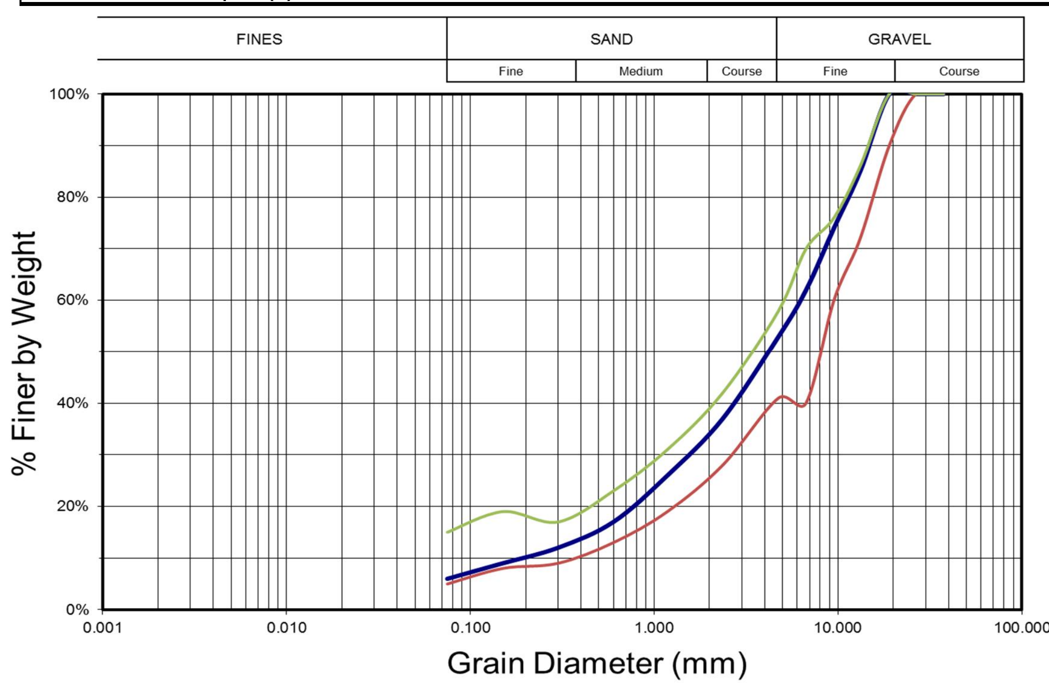
C1. 0 % RAP Mix Design

MIX DESIGN PROPORTIONS CALCULATION			
Date:	15-08-2015	Binder Type	C600
Student:	Athar Asghar	RAP - Binder (%)	0
Job No.	USQ Project	Design (%)	4.7
Mix Type:	0% RAP		
Tray Number		0% RAP	
Final Mass Tray + Dry Sample	M(g)	4278.5	
Mass of Dry Sample	M(g)	4278.5	
Oven Test Temperature			
Determination of Sieve Analysis			
A.S Sieve Size	Cumulative Mass Retained M(g)	% Passing P = 100 - ((100 X M/T)	Specification Limits
37.5 mm	0	100.0	
26.5 mm	0	100.0	100
19.0 mm	0	100.0	90-100
13.2 mm	641.0	85.0	72-86
9.5 mm	1112.4	74.0	60-76
6.7 mm	1625.8	62.0	40-70
4.75 mm	2010.9	53.0	41-58
2.36 mm	2695.5	37.0	28-42
1.18 mm	3166.0	26.0	19-31
0.60 mm	3551.1	17.0	13-23
0.30 mm	3765.1	12.0	09--17
0.15 mm	3893.4	9.0	08--19
0.075 mm	4021.7	6.0	05--15
Mass of Test Sample (T)		4278.5	



C2. 15%, 30%, 40%, 50%, 60% RAP Mix Design

MIX DESIGN PROPORTIONS CALCULATION			
Date:	15-08-2015	Binder Type	C320
Student:	Athar Asghar	RAP - Binder (%)	3.4
Job No.	USQ Project	Design (%)	4.7
Mix Type:	RAP		
Tray Number		15% ,30%, 40%, 50%, 60% RAP	
Final Mass Tray + Dry Sample	M(g)	4278.5	
Mass of Dry Sample	M(g)	4278.5	
Oven Test Temperature			
Determination of Sieve Analysis			
A.S Sieve Size	Cumulative Mass Retained M(g)	% Passing P = 100 - ((100 X M/T)	Specification Limits
37.5 mm	0	100.0	
26.5 mm	0	100.0	100
19.0 mm	0	100.0	90-100
13.2 mm	641.0	85.0	72-86
9.5 mm	1112.4	74.0	60-76
6.7 mm	1625.8	62.0	40-70
4.75 mm	2010.9	53.0	41-58
2.36 mm	2695.5	37.0	28-42
1.18 mm	3166.0	26.0	19-31
0.60 mm	3551.1	17.0	13-23
0.30 mm	3765.1	12.0	09--17
0.15 mm	3893.4	9.0	08--19
0.075 mm	4021.7	6.0	05--15
Mass of Test Sample (T)		4278.5	



Appendix D – Resilient Modulus Test Data

0 %(A) RAP Resilient Modulus Test Results

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. lvdts only, assumed Poisson's ratio)
Data fileName: E:\New folder\Sample 0A.D003
Template file name: C:\Users\user\Desktop\Templates UTM 2015 april\Dinesh and Aki\Indirect tensile modulus test project August1.P003
Test date & time: 26/08/2015 9:48:46 AM
Project: Evaluation of the strength Characteristics of Recycled Bituminous Pavement
Operator: Athar Asghar
Comments:

Setup Parameters

Target temperature (°C): 25
Loading pulse width (ms): 250
Pulse repetition period (ms): 3000
Conditioning pulse count: 5
Peak loading force (N): 2000
Estimated Poisson's ratio: 0.4
Seating force: AASHTO TP31 (10% of peak)

Specimen Information

Identification: Sample 0A
Remarks...

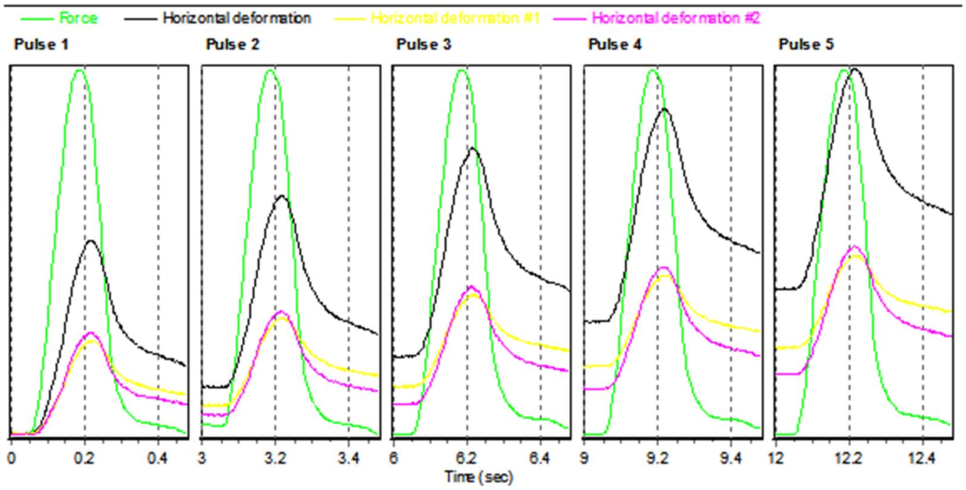
Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	60.0	60.2	60.5	60.5			60.3	0.2
Diameter (mm)	101.7	101.7	101.8	101.7			101.7	0.0

Cross-sectional area (mm²): 8126.5

Test Results

Conditioning pulses: 5
Core temperature (°C): 30.1
Skin temperature (°C): 30.2
Permit horiz1 def'n/pulse (µm): 2.310000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	5727	5155	5013	4853	4792	5108	334.55	8.14
Total recoverable horiz. deform. (µm)	4.70	5.20	5.56	5.78	5.92	5.43	0.44	8.08
Peak loading force (N)	2001	1943	2009	2004	2020	1996	26.96	1.35
Recoverable horiz. deform. #1 (µm)	2.08	2.25	2.32	2.32	2.34	2.26	0.10	4.20
Recoverable horiz. deform. #2 (µm)	2.62	2.95	3.24	3.46	3.58	3.17	0.35	11.01
Seating force (N)	226	221	189	189	192	203	16.20	7.96



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0 %(B) RAP Resilient Modulus Test Results

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. lvdts only, assumed Poisson's ratio)
Data fileName: E:\New folder\Sample 0B.D003
Template file name: C:\Users\user\Desktop\Templates UTM 2015 april\Dinesh and Aki\Indirect tensile modulus test project August1.P003
Test date & time: 26/08/2015 9:58:56 AM
Project: Evaluation of the strength Characteristics of Recycled Bituminous Pavement
Operator: Athar Asghar
Comments:

Setup Parameters

Target temperature (°C): 25
Loading pulse width (ms): 250
Pulse repetition period (ms): 3000
Conditioning pulse count: 5
Peak loading force (N): 2000
Estimated Poisson's ratio: 0.4
Seating force: AASHTO TP31 (10% of peak)

Specimen Information

Identification: Sample 0B
Remarks...

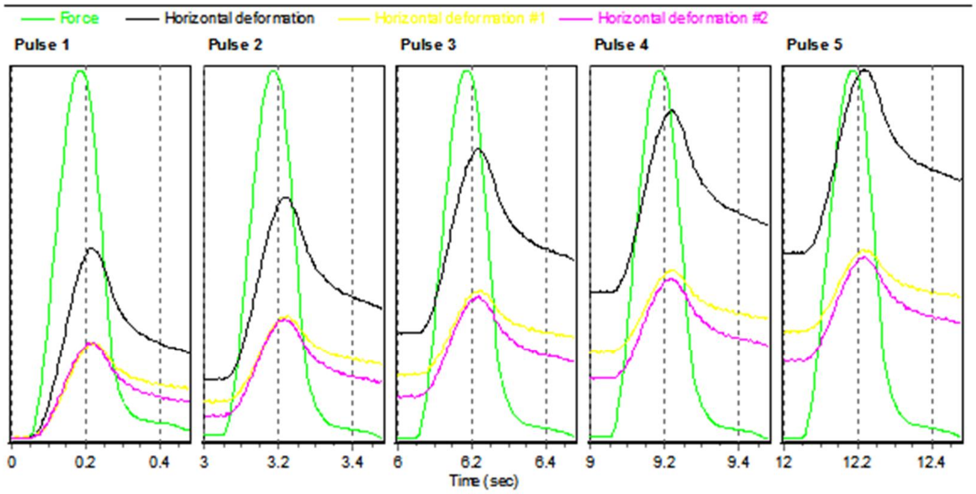
Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	61.1	60.9	60.8	60.6			60.9	0.2
Diameter (mm)	101.7	101.9	101.8	101.7			101.8	0.1

Cross-sectional area (mm²): 8139.3

Test Results

Conditioning pulses: 5
Core temperature (°C): 29.6
Skin temperature (°C): 29.8
Permit horiz1 def'n/pulse (µm): 3.232000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	5855	5567	5428	5391	5403	5529	174.74	3.86
Total recoverable horiz. deform. (µm)	4.72	4.88	5.07	5.07	5.09	4.97	0.15	2.92
Peak loading force (N)	2083	2025	2039	2025	2037	2042	21.37	1.05
Recoverable horiz. deform. #1 (µm)	2.12	2.12	2.18	2.18	2.16	2.15	0.03	1.26
Recoverable horiz. deform. #2 (µm)	2.60	2.76	2.89	2.90	2.94	2.82	0.12	4.32
Seating force (N)	194	209	208	184	208	200	10.06	5.02



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0 %(C) RAP Resilient Modulus Test Results

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. lvdts only, assumed Poisson's ratio)
Data fileName: E:\New folder\Sample 0C.D003
Template file name: C:\Users\user\Desktop\Templates UTM 2015 april\Dinesh and Aki\Indirect tensile modulus test project August1.P003
Test date & time: 26/08/2015 10:05:06 AM
Project: Evaluation of the strength Characteristics of Recycled Bituminous Pavement
Operator: Athar Asghar
Comments:

Setup Parameters

Target temperature (°C): 25
Loading pulse width (ms): 250
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 2000
Estimated Poisson's ratio: 0.4

Seating force: AASHTO TP31 (10% of peak)

Specimen Information

Identification: Sample 0C
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	60.8	60.6	61.1	60.9			60.9	0.2
Diameter (mm)	101.9	101.7	101.7	101.8			101.8	0.1

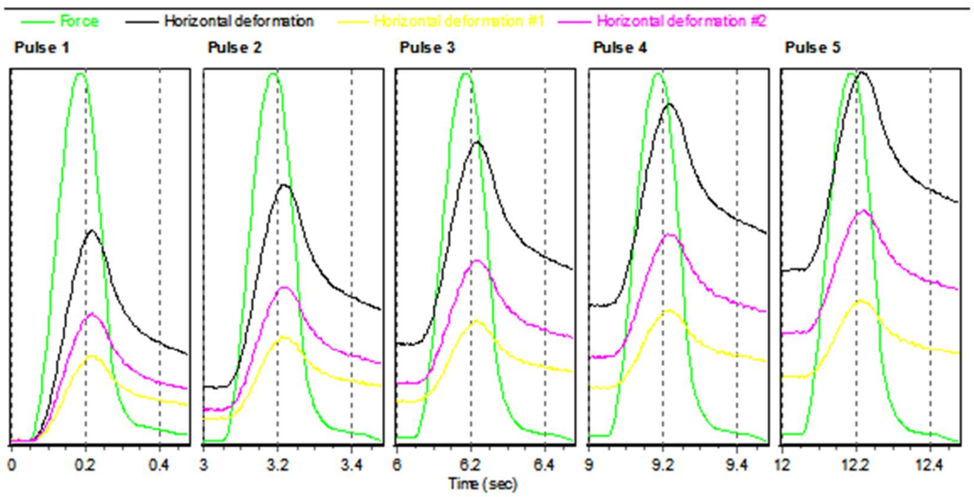
Cross-sectional area (mm²): 8139.3

Test Results

Conditioning pulses: 5
Core temperature (°C): 29.7
Skin temperature (°C): 29.1

Perm't horiz1 def'n/pulse (µm): 2.763000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	5181	5039	4918	4884	4792	4965	141.20	3.56
Total recoverable horiz. deform. (µm)	5.42	5.50	5.65	5.72	5.77	5.61	0.13	2.37
Peak loading force (N)	2058	2032	2012	2008	1987	2020	24.03	1.19
Recoverable horiz. deform. #1 (µm)	2.15	2.17	2.30	2.31	2.35	2.26	0.08	3.64
Recoverable horiz. deform. #2 (µm)	3.27	3.33	3.35	3.41	3.42	3.36	0.05	1.61
Seating force (N)	187	189	212	210	209	201	11.08	5.50



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15 %(A) RAP Resilient Modulus Test Results

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. lvdts only, assumed Poisson's ratio)
Data fileName: E:\New folder\Sample 15A.D003
Template file name: C:\Users\user\Desktop\Templates UTM 2015 april\Dinesh and Aki\Indirect tensile modulus test project August1.P003
Test date & time: 26/08/2015 9:10:46 AM
Project: Evaluation of the strength Characteristics of Recycled Bituminous Pavement
Operator: Athar Asghar
Comments:

Setup Parameters

Target temperature (°C): 25
Loading pulse width (ms): 250
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 2000
Estimated Poisson's ratio: 0.4

Seating force: AASHTO TP31 (10% of peak)

Specimen Information

Identification: Sample 15A
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	71.4	70.8	71.1	71.6			71.2	0.4
Diameter (mm)	101.7	101.5	101.5	101.8			101.6	0.2

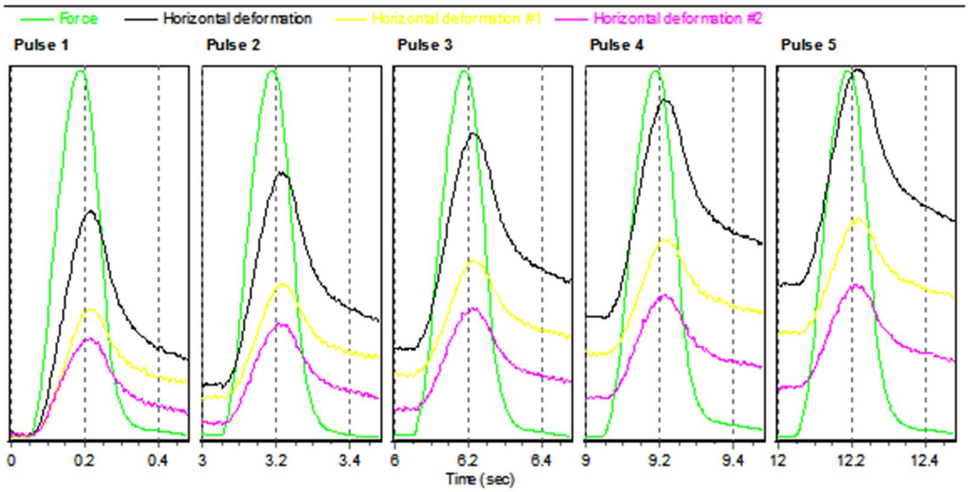
Cross-sectional area (mm²): 8112.9

Test Results

Conditioning pulses: 5
Core temperature (°C): 29.5
Skin temperature (°C): 29.4

Permit horiz1 def'n/pulse (µm): 1.053000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	7363	7108	6901	6910	6655	6988	236.31	3.38
Total recoverable horiz. deform. (µm)	2.63	2.65	2.74	2.79	2.87	2.74	0.09	3.30
Peak loading force (N)	2059	2000	2010	2051	2032	2030	22.74	1.12
Recoverable horiz. deform. #1 (µm)	1.34	1.36	1.38	1.40	1.45	1.38	0.04	2.68
Recoverable horiz. deform. #2 (µm)	1.29	1.28	1.36	1.40	1.42	1.35	0.06	4.12
Seating force (N)	208	206	209	194	184	200	9.91	4.95



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15 %(B) RAP Resilient Modulus Test Results

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. lvdts only, assumed Poisson's ratio)
Data fileName: E:\New folder\Sample 15B.D003
Template file name: C:\Users\user\Desktop\Templates UTM 2015 april\Dinesh and Aki\Indirect tensile modulus test project August1.P003
Test date & time: 26/08/2015 9:27:32 AM
Project: Evaluation of the strength Characteristics of Recycled Bituminous Pavement
Operator: Athar Asghar
Comments:

Setup Parameters

Target temperature (°C): 25
Loading pulse width (ms): 250
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 2000
Estimated Poisson's ratio: 0.4

Seating force: AASHTO TP31 (10% of peak)

Specimen Information

Identification: Sample 15B
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	67.4	67.1	68.0	67.8			67.6	0.4
Diameter (mm)	101.7	101.6	101.7	101.7			101.7	0.1

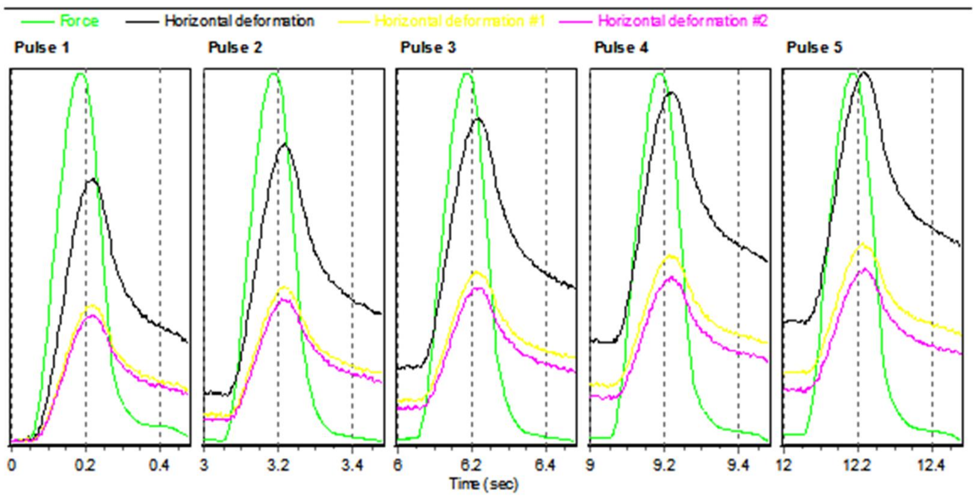
Cross-sectional area (mm²): 8118.9

Test Results

Conditioning pulses: 5
Core temperature (°C): 29.5
Skin temperature (°C): 29.5

Perm't horiz'l def'n/pulse (µm): 0.760400

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	6875	6415	6444	6257	6110	6420	257.20	4.01
Total recoverable horiz. deform. (µm)	3.02	3.14	3.12	3.23	3.29	3.16	0.09	2.90
Peak loading force (N)	2094	2034	2030	2037	2025	2044	25.24	1.23
Recoverable horiz. deform. #1 (µm)	1.54	1.61	1.58	1.67	1.67	1.61	0.05	3.19
Recoverable horiz. deform. #2 (µm)	1.48	1.53	1.54	1.56	1.61	1.55	0.04	2.74
Seating force (N)	195	205	205	206	207	203	4.47	2.20



15 %(C) RAP Resilient Modulus Test Results

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. lvdts only, assumed Poisson's ratio)
Data fileName: E:\New folder\Sample 15C.D003
Template file name: C:\Users\user\Desktop\Templates UTM 2015 april\Dinesh and Aki\Indirect tensile modulus test project August1.P003
Test date & time: 26/08/2015 9:39:34 AM
Project: Evaluation of the strength Characteristics of Recycled Bituminous Pavement
Operator: Athar Asghar
Comments:

Setup Parameters

Target temperature (°C): 25
Loading pulse width (ms): 250
Pulse repetition period (ms): 3000
Conditioning pulse count: 5
Peak loading force (N): 2000
Estimated Poisson's ratio: 0.4
Seating force: AASHTO TP31 (10% of peak)

Specimen Information

Identification: Sample 15C
Remarks...

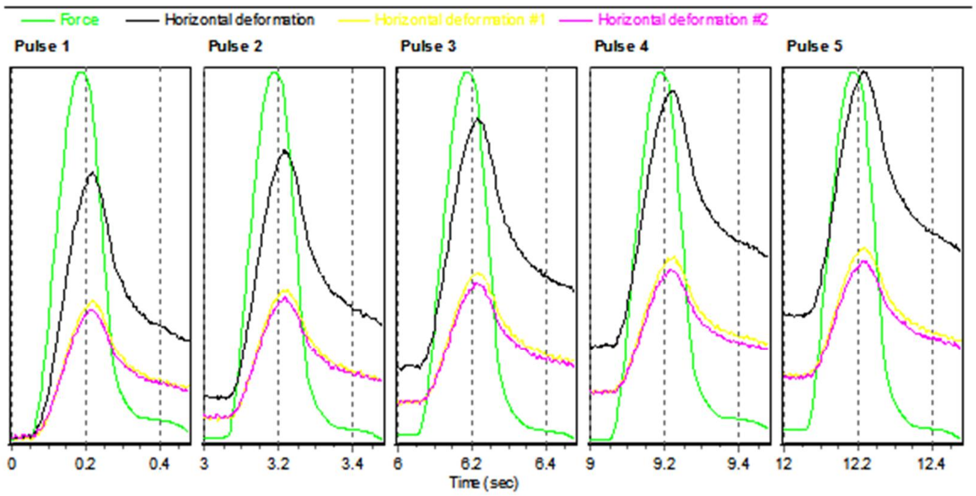
Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	61.7	62.0	61.6	61.5			61.7	0.2
Diameter (mm)	101.3	101.6	101.6	101.6			101.5	0.2

Cross-sectional area (mm²): 8098.1

Test Results

Conditioning pulses: 5
Core temperature (°C): 29.6
Skin temperature (°C): 29.7
Perm't horiz1 def'n/pulse (µm): 0.870800

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	6232	6214	5926	6225	5815	6082	176.55	2.90
Total recoverable horiz. deform. (µm)	3.52	3.42	3.56	3.50	3.58	3.51	0.06	1.57
Peak loading force (N)	2018	1956	1940	2006	1916	1967	38.84	1.97
Recoverable horiz. deform. #1 (µm)	1.86	1.75	1.86	1.84	1.89	1.84	0.05	2.67
Recoverable horiz. deform. #2 (µm)	1.65	1.67	1.70	1.66	1.69	1.67	0.02	0.92
Seating force (N)	204	171	222	195	216	202	17.92	8.89



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30 %(A) RAP Resilient Modulus Test Results

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. lvdts only, assumed Poisson's ratio)
Data fileName: E:\New folder\Sample 30A.D003
Template file name: C:\Users\user\Desktop\Templates UTM 2015 april\Dinesh and Aki\Indirect tensile modulus test project August1.P003
Test date & time: 26/08/2015 10:12:01 AM
Project: Evaluation of the strength Characteristics of Recycled Bituminous Pavement
Operator: Athar Asghar
Comments:

Setup Parameters

Target temperature (°C): 25
Loading pulse width (ms): 250
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 2000
Estimated Poisson's ratio: 0.4

Seating force: AASHTO TP31 (10% of peak)

Specimen Information

Identification: Sample 30A
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	63.3	64.0	63.9	63.3			63.6	0.4
Diameter (mm)	101.6	101.6	101.5	101.6			101.6	0.0

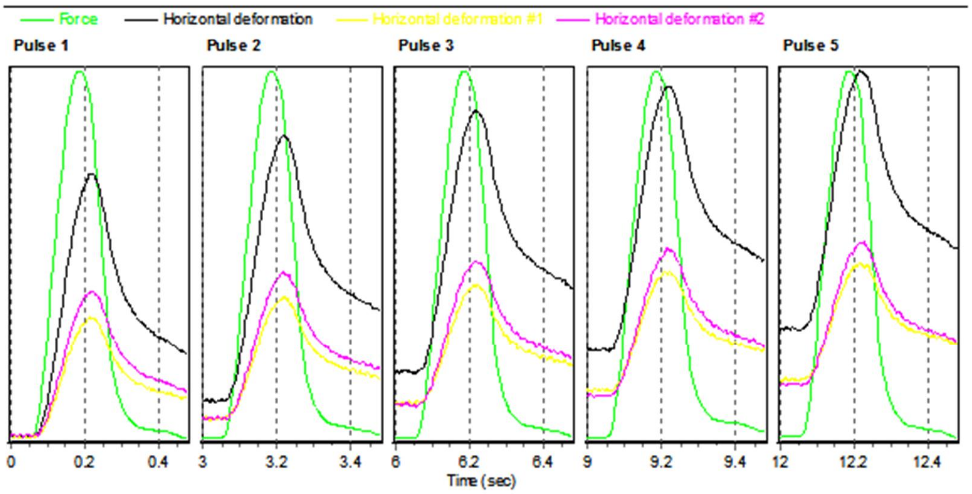
Cross-sectional area (mm²): 8103.7

Test Results

Conditioning pulses: 5
Core temperature (°C): 29.7
Skin temperature (°C): 29.7

Permit horiz1 def'n/pulse (µm): 0.933400

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	4934	4725	4679	4634	4602	4715	117.38	2.49
Total recoverable horiz. deform. (µm)	4.25	4.46	4.48	4.59	4.55	4.47	0.12	2.60
Peak loading force (N)	1994	2004	1993	2020	1989	2000	11.03	0.55
Recoverable horiz. deform. #1 (µm)	1.88	1.97	1.97	2.02	2.04	1.98	0.06	2.80
Recoverable horiz. deform. #2 (µm)	2.37	2.49	2.52	2.56	2.51	2.49	0.06	2.58
Seating force (N)	179	199	199	196	199	194	7.75	3.99



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30 %(B) RAP Resilient Modulus Test Results

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. lvdts only, assumed Poisson's ratio)
Data fileName: E:\New folder\Sample 30B.D003
Template file name: C:\Users\user\Desktop\Templates UTM 2015 april\Dinesh and Aki\Indirect tensile modulus test project August1.P003
Test date & time: 26/08/2015 10:30:37 AM
Project: Evaluation of the strength Characteristics of Recycled Bituminous Pavement
Operator: Athar Asghar
Comments:

Setup Parameters

Target temperature (°C): 25
Loading pulse width (ms): 250
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 2000
Estimated Poisson's ratio: 0.4

Seating force: AASHTO TP31 (10% of peak)

Specimen Information

Identification: Sample 30B
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	74.0	74.0	72.5	73.5			73.5	0.7
Diameter (mm)	101.7	101.7	101.9	101.6			101.7	0.1

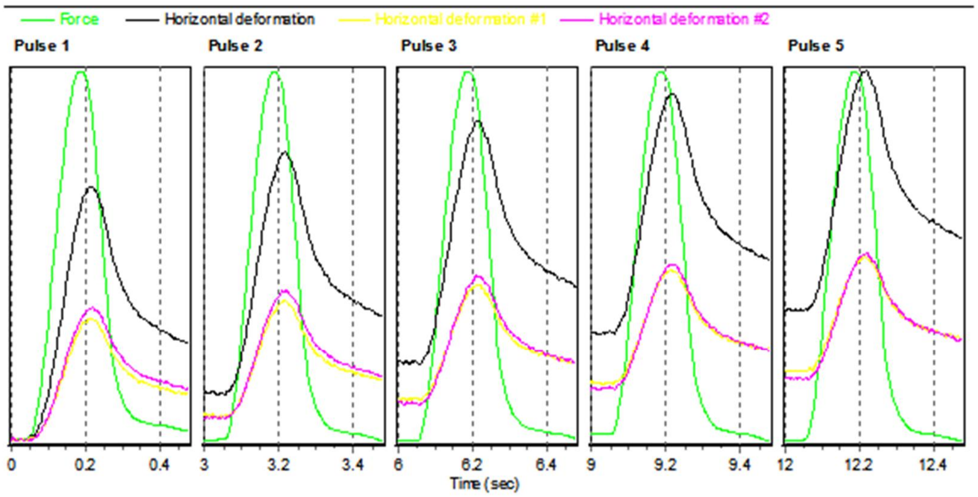
Cross-sectional area (mm²): 8127.3

Test Results

Conditioning pulses: 5
Core temperature (°C): 30.2
Skin temperature (°C): 30.2

Permit horiz1 def'n/pulse (µm): 1.120000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	5005	4777	4763	4574	4635	4751	148.32	3.12
Total recoverable horiz. deform. (µm)	3.73	3.80	3.82	3.92	3.90	3.83	0.07	1.74
Peak loading force (N)	2049	1990	1997	1965	1980	1996	28.61	1.43
Recoverable horiz. deform. #1 (µm)	1.73	1.79	1.77	1.85	1.82	1.79	0.04	2.20
Recoverable horiz. deform. #2 (µm)	2.00	2.01	2.05	2.07	2.08	2.04	0.03	1.54
Seating force (N)	197	186	186	216	184	194	12.11	6.25



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30 %(C) RAP Resilient Modulus Test Results

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. lvdts only, assumed Poisson's ratio)
Data fileName: E:\New folder\Sample 30C.D003
Template file name: C:\Users\user\Desktop\Templates UTM 2015 april\Dinesh and Aki\Indirect tensile modulus test project August1.P003
Test date & time: 26/08/2015 10:39:56 AM
Project: Evaluation of the strength Characteristics of Recycled Bituminous Pavement
Operator: Athar Asghar
Comments:

Setup Parameters

Target temperature (°C): 25
Loading pulse width (ms): 250
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 2000
Estimated Poisson's ratio: 0.4

Seating force: AASHTO TP31 (10% of peak)

Specimen Information

Identification: Sample 30C
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	70.7	69.0	70.1	70.7			70.1	0.8
Diameter (mm)	101.5	101.5	101.6	101.8			101.6	0.2

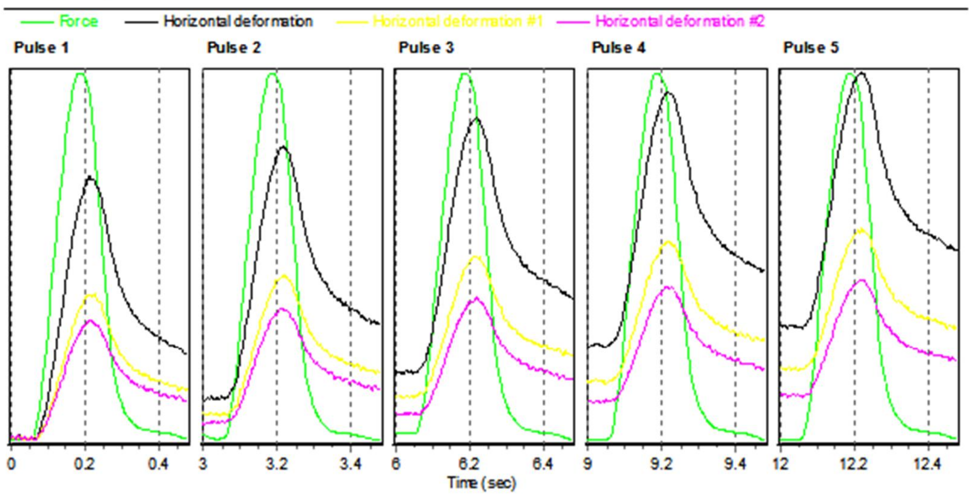
Cross-sectional area (mm²): 8110.5

Test Results

Conditioning pulses: 5
Core temperature (°C): 29.5
Skin temperature (°C): 29.7

Perm't horiz1 def'n/pulse (µm): 0.721000

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	6507	6274	6182	6132	6183	6256	133.60	2.14
Total recoverable horiz. deform. (µm)	3.00	3.05	3.09	3.16	3.13	3.09	0.06	1.83
Peak loading force (N)	2044	2000	1996	2026	2027	2019	18.10	0.90
Recoverable horiz. deform. #1 (µm)	1.61	1.63	1.68	1.69	1.69	1.66	0.03	2.01
Recoverable horiz. deform. #2 (µm)	1.39	1.41	1.40	1.47	1.44	1.42	0.03	1.90
Seating force (N)	184	200	223	186	186	196	14.78	7.54



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40 %(A) RAP Resilient Modulus Test Results

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. lvdts only, assumed Poisson's ratio)
Data fileName: E:\New folder\Sample 40A.D003
Template file name: C:\Users\user\Desktop\Templates UTM 2015 april\Dinesh and Aki\Indirect tensile modulus test project August1.P003
Test date & time: 26/08/2015 10:47:41 AM
Project: Evaluation of the strength Characteristics of Recycled Bituminous Pavement
Operator: Athar Asghar
Comments:

Setup Parameters

Target temperature (°C): 25
Loading pulse width (ms): 250
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 2000
Estimated Poisson's ratio: 0.4

Seating force: AASHTO TP31 (10% of peak)

Specimen Information

Identification: Sample 40A
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	63.6	63.6	63.6	63.9			63.7	0.2
Diameter (mm)	101.6	101.6	101.6	101.5			101.6	0.1

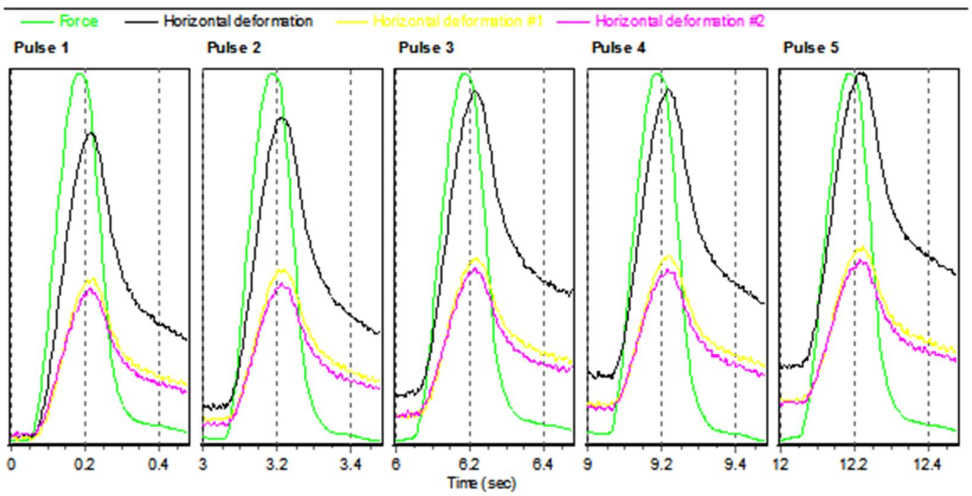
Cross-sectional area (mm²): 8100.9

Test Results

Conditioning pulses: 5
Core temperature (°C): 29.6
Skin temperature (°C): 29.8

Permit horiz1 defl'n/pulse (µm): 0.406700

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	6936	6571	6668	6392	6735	6661	179.66	2.70
Total recoverable horiz. deform. (µm)	3.07	3.10	3.15	3.11	3.06	3.10	0.03	1.05
Peak loading force (N)	2021	1935	1997	1891	1961	1961	45.80	2.34
Recoverable horiz. deform. #1 (µm)	1.53	1.63	1.60	1.60	1.54	1.58	0.04	2.32
Recoverable horiz. deform. #2 (µm)	1.54	1.47	1.56	1.51	1.52	1.52	0.03	1.83
Seating force (N)	189	196	200	221	202	202	10.62	5.26



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40 %(B) RAP Resilient Modulus Test Results

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. lvdts only, assumed Poisson's ratio)
Data fileName: E:\New folder\Sample 40B.D003
Template file name: C:\Users\user\Desktop\Templates UTM 2015 april\Dinesh and Aki\Indirect tensile modulus test project August1.P003
Test date & time: 26/08/2015 11:04:29 AM
Project: Evaluation of the strength Characteristics of Recycled Bituminous Pavement
Operator: Athar Asghar
Comments:

Setup Parameters

Target temperature (°C): 25
Loading pulse width (ms): 250
Pulse repetition period (ms): 3000
Conditioning pulse count: 5
Peak loading force (N): 2000
Estimated Poisson's ratio: 0.4
Seating force: AASHTO TP31 (10% of peak)

Specimen Information

Identification: Sample 40B
Remarks...

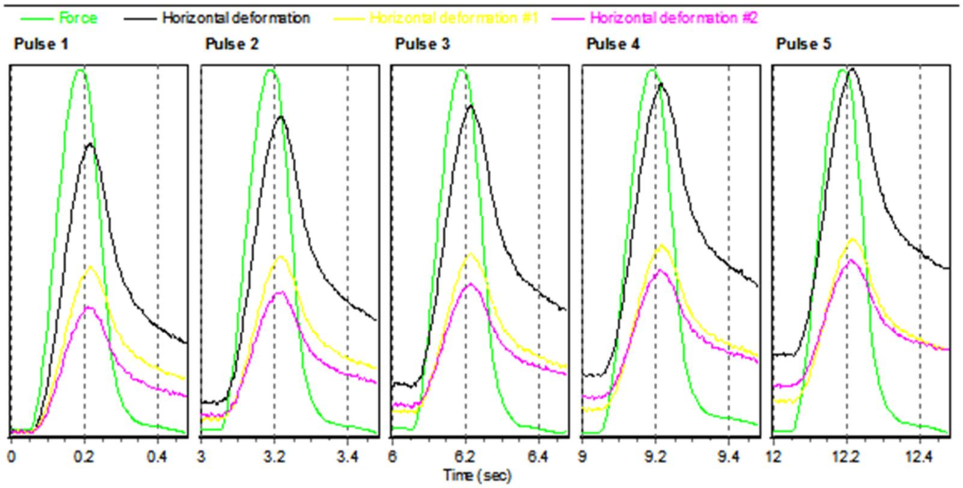
Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	64.2	64.3	65.3	64.2			64.5	0.6
Diameter (mm)	101.0	101.6	101.5	101.6			101.4	0.2

Cross-sectional area (mm²): 8077.0

Test Results

Conditioning pulses: 5
Core temperature (°C): 29.3
Skin temperature (°C): 29.5
Permit horiz1 defn/pulse (µm): 0.588400

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	4901	4701	4655	4780	4614	4730	101.56	2.15
Total recoverable horiz. deform. (µm)	4.31	4.46	4.43	4.49	4.56	4.45	0.08	1.80
Peak loading force (N)	2035	2020	1988	2065	2024	2026	25.00	1.23
Recoverable horiz. deform. #1 (µm)	2.54	2.57	2.57	2.58	2.63	2.58	0.03	1.14
Recoverable horiz. deform. #2 (µm)	1.77	1.89	1.87	1.90	1.93	1.87	0.05	2.88
Seating force (N)	220	216	207	192	217	211	10.03	4.76



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40 %(C) RAP Resilient Modulus Test Results

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. lvdts only, assumed Poisson's ratio)
Data fileName: E:\New folder\Sample 40C.D003
Template file name: C:\Users\user\Desktop\Templates UTM 2015 april\Dinesh and Aki\Indirect tensile modulus test project August1.P003
Test date & time: 26/08/2015 11:11:59 AM
Project: Evaluation of the strength Characteristics of Recycled Bituminous Pavement
Operator: Athar Asghar
Comments:

Setup Parameters

Target temperature (°C): 25
Loading pulse width (ms): 250
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 2000
Estimated Poisson's ratio: 0.4

Seating force: AASHTO TP31 (10% of peak)

Specimen Information

Identification: Sample 40C
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	65.4	65.3	65.7	65.4			65.4	0.2
Diameter (mm)	101.5	101.7	101.7	101.7			101.6	0.1

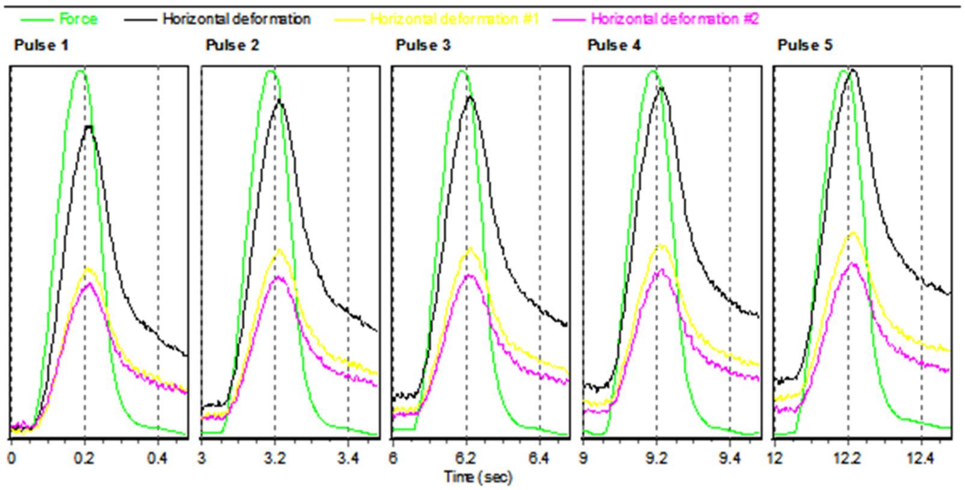
Cross-sectional area (mm²): 8112.9

Test Results

Conditioning pulses: 5
Core temperature (°C): 29.3
Skin temperature (°C): 29.6

Permit horiz1 def'n/pulse (µm): 0.223600

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	7334	6974	7145	7113	7041	7121	121.71	1.71
Total recoverable horiz. deform. (µm)	2.81	2.97	2.86	2.87	2.98	2.90	0.07	2.25
Peak loading force (N)	2013	2020	1994	1996	2050	2015	20.19	1.00
Recoverable horiz. deform. #1 (µm)	1.47	1.60	1.51	1.51	1.55	1.53	0.04	2.90
Recoverable horiz. deform. #2 (µm)	1.34	1.37	1.35	1.36	1.43	1.37	0.03	2.20
Seating force (N)	219	215	213	200	207	211	6.65	3.15



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50 %(A) RAP Resilient Modulus Test Results

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. lvdts only, assumed Poisson's ratio)
Data fileName: E:\New folder\Sample 50A.D003
Template file name: C:\Users\user\Desktop\Templates UTM 2015 april\Dinesh and Aki\Indirect tensile modulus test project August1.P003
Test date & time: 26/08/2015 11:19:25 AM
Project: Evaluation of the strength Characteristics of Recycled Bituminous Pavement
Operator: Athar Asghar
Comments:

Setup Parameters

Target temperature (°C): 25
Loading pulse width (ms): 250
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 2000
Estimated Poisson's ratio: 0.4

Seating force: AASHTO TP31 (10% of peak)

Specimen Information

Identification: Sample 50A
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	60.2	60.3	60.6	60.2			60.3	0.2
Diameter (mm)	101.8	101.6	101.5	101.7			101.7	0.1

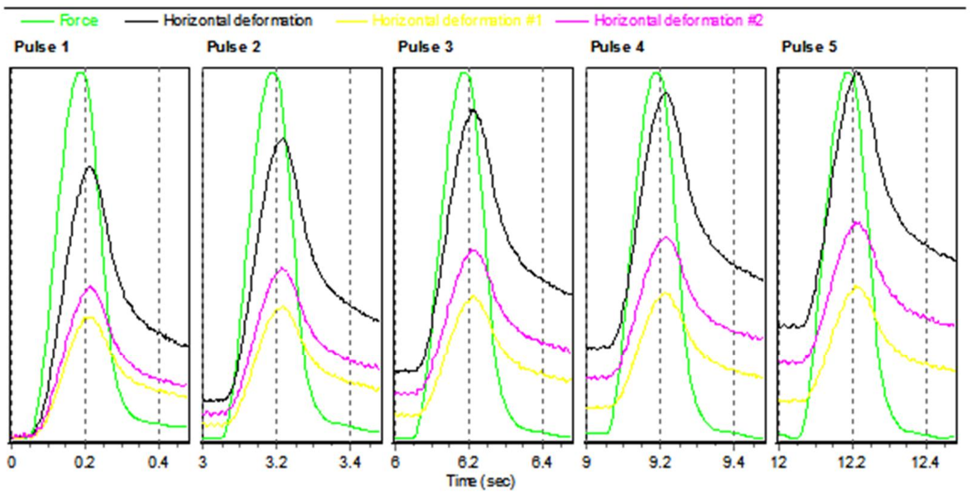
Cross-sectional area (mm²): 8116.1

Test Results

Conditioning pulses: 5
Core temperature (°C): 29.4
Skin temperature (°C): 29.6

Perm't horiz'l def'n/pulse (µm): 0.909700

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	5401	5337	5136	5207	4997	5216	143.89	2.76
Total recoverable horiz. deform. (µm)	4.26	4.25	4.35	4.23	4.39	4.30	0.06	1.45
Peak loading force (N)	2069	2041	2012	1984	1973	2016	35.67	1.77
Recoverable horiz. deform. #1 (µm)	1.94	1.94	2.03	1.98	2.02	1.98	0.04	1.97
Recoverable horiz. deform. #2 (µm)	2.32	2.30	2.32	2.26	2.37	2.31	0.04	1.52
Seating force (N)	191	188	217	215	206	203	11.98	5.89



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50 %(B) RAP Resilient Modulus Test Results

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. lvdts only, assumed Poisson's ratio)
Data fileName: E:\New folder\Sample 50B.D003
Template file name: C:\Users\user\Desktop\Templates UTM 2015 april\Dinesh and Aki\Indirect tensile modulus test project August1.P003
Test date & time: 26/08/2015 11:25:46 AM
Project: Evaluation of the strength Characteristics of Recycled Bituminous Pavement
Operator: Athar Asghar
Comments:

Setup Parameters

Target temperature (°C): 25
Loading pulse width (ms): 250
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 2000
Estimated Poisson's ratio: 0.4

Seating force: AASHTO TP31 (10% of peak)

Specimen Information

Identification: Sample 50B
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	60.6	61.1	61.1	60.7			60.9	0.2
Diameter (mm)	101.6	101.4	101.6	101.7			101.6	0.1

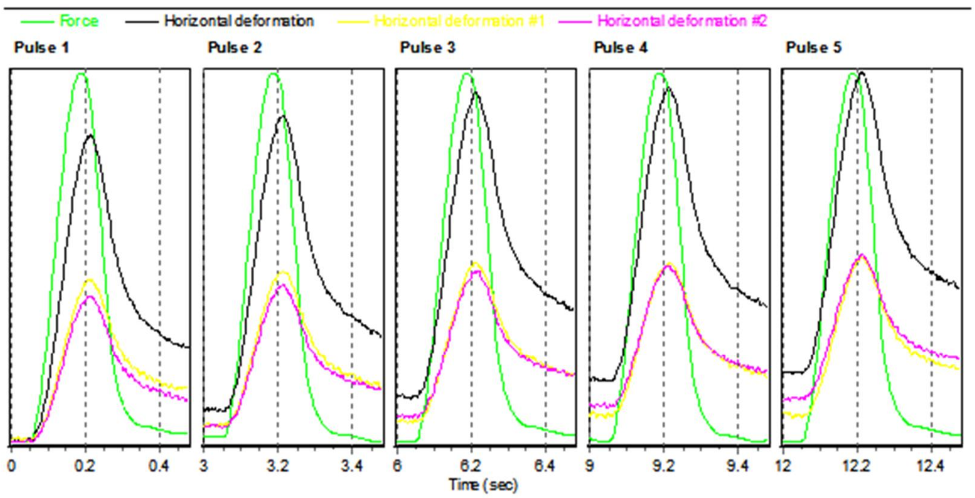
Cross-sectional area (mm²): 8103.3

Test Results

Conditioning pulses: 5
Core temperature (°C): 29.3
Skin temperature (°C): 29.5

Permit horiz1 defl'n/pulse (µm): 0.457400

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	6150	5862	5885	5781	5971	5930	125.68	2.12
Total recoverable horiz. deform. (µm)	3.65	3.71	3.79	3.76	3.73	3.73	0.05	1.26
Peak loading force (N)	2040	1973	2026	1974	2021	2007	27.72	1.38
Recoverable horiz. deform. #1 (µm)	1.93	1.97	2.01	1.98	1.95	1.97	0.03	1.44
Recoverable horiz. deform. #2 (µm)	1.73	1.73	1.78	1.78	1.77	1.76	0.02	1.40
Seating force (N)	188	214	190	197	192	196	9.34	4.76



Industrial Process Controls Global Ltd UTS003 Ver:1.41 (1.41)
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50 %(C) RAP Resilient Modulus Test Results

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. lvdts only, assumed Poisson's ratio)
Data fileName: E:\New folder\Sample 50C.D003
Template file name: C:\Users\user\Desktop\Templates UTM 2015 april\Dinesh and Aki\Indirect tensile modulus test project August1.P003
Test date & time: 26/08/2015 11:32:24 AM
Project: Evaluation of the strength Characteristics of Recycled Bituminous Pavement
Operator: Athar Asghar
Comments:

Setup Parameters

Target temperature (°C): 25
Loading pulse width (ms): 250
Pulse repetition period (ms): 3000
Conditioning pulse count: 5
Peak loading force (N): 2000
Estimated Poisson's ratio: 0.4
Seating force: AASHTO TP31 (10% of peak)

Specimen Information

Identification: Sample 50C
Remarks...

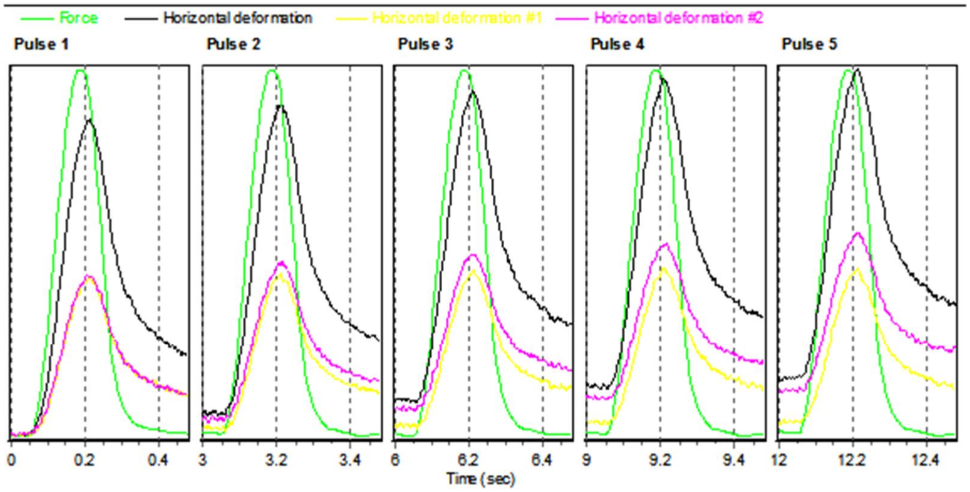
Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	66.7	66.3	66.7	66.3			66.5	0.3
Diameter (mm)	101.8	101.6	101.7	101.6			101.7	0.1

Cross-sectional area (mm²): 8124.1

Test Results

Conditioning pulses: 5
Core temperature (°C): 29.3
Skin temperature (°C): 29.5
Permit horiz1 def'n/pulse (µm): 0.287300

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	6368	6158	6211	6034	6069	6168	118.12	1.92
Total recoverable horiz. deform. (µm)	3.16	3.19	3.17	3.25	3.23	3.20	0.03	1.05
Peak loading force (N)	1997	1951	1953	1943	1945	1958	19.75	1.01
Recoverable horiz. deform. #1 (µm)	1.64	1.63	1.64	1.68	1.62	1.64	0.02	1.08
Recoverable horiz. deform. #2 (µm)	1.52	1.56	1.53	1.57	1.61	1.56	0.03	2.07
Seating force (N)	189	207	200	207	208	202	7.15	3.53



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60 %(A) RAP Resilient Modulus Test Results

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. lvdts only, assumed Poisson's ratio)
Data fileName: E:\New folder\Sample 60A.D003
Template file name: C:\Users\user\Desktop\Templates UTM 2015 april\Dinesh and Akil\Indirect tensile modulus test project August1.P003
Test date & time: 26/08/2015 11:38:32 AM
Project: Evaluation of the strength Characteristics of Recycled Bituminous Pavement
Operator: Athar Asghar
Comments:

Setup Parameters

Target temperature (°C): 25
Loading pulse width (ms): 250
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 2000
Estimated Poisson's ratio: 0.4

Seating force: AASHTO TP31 (10% of peak)

Specimen Information

Identification: Sample 60A
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	66.0	66.0	66.1	65.8			66.0	0.1
Diameter (mm)	100.9	101.1	101.7	101.6			101.3	0.4

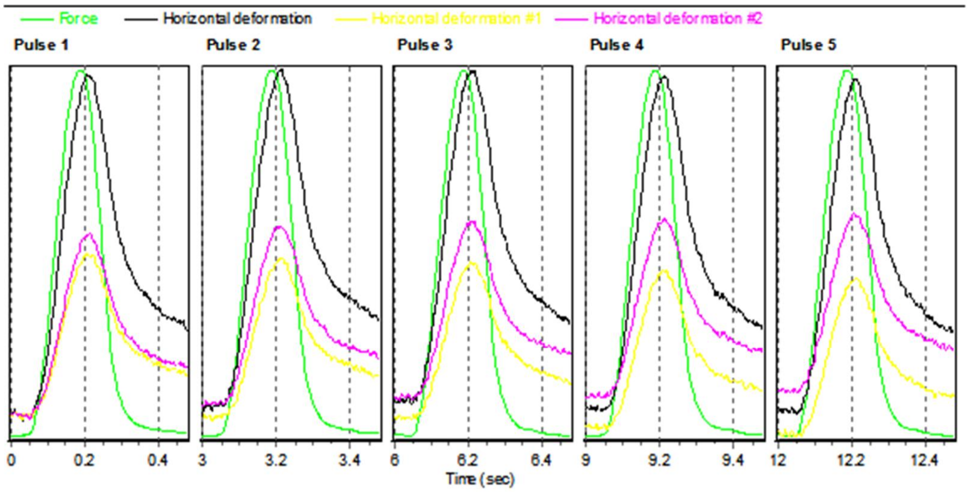
Cross-sectional area (mm²): 8061.5

Test Results

Conditioning pulses: 5
Core temperature (°C): 29.2
Skin temperature (°C): 29.5

Perm't horiz1 def'n/pulse (µm): 0.023160

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	6829	6774	6576	6741	6776	6739	86.47	1.28
Total recoverable horiz. deform. (µm)	3.02	3.02	3.08	3.02	2.99	3.03	0.03	0.96
Peak loading force (N)	2031	2013	1995	2007	1997	2009	13.06	0.65
Recoverable horiz. deform. #1 (µm)	1.48	1.46	1.48	1.45	1.44	1.46	0.02	1.14
Recoverable horiz. deform. #2 (µm)	1.54	1.55	1.60	1.58	1.55	1.56	0.02	1.27
Seating force (N)	198	198	204	200	203	201	2.40	1.19



Industrial Process Controls Global Ltd UTS003 Ver:1.41 (1.41)
Printed 26/08/2015 12:11:45 PM

60 %(B) RAP Resilient Modulus Test Results

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. lvdts only, assumed Poisson's ratio)
Data fileName: E:\New folder\Sample 60B.D003
Template file name: C:\Users\user\Desktop\Templates UTM 2015 april\Dinesh and Aki\Indirect tensile modulus test project August1.P003
Test date & time: 26/08/2015 11:44:28 AM
Project: Evaluation of the strength Characteristics of Recycled Bituminous Pavement
Operator: Athar Asghar
Comments:

Setup Parameters

Target temperature (°C): 25
Loading pulse width (ms): 250
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 2000
Estimated Poisson's ratio: 0.4

Seating force: AASHTO TP31 (10% of peak)

Specimen Information

Identification: Sample 60B
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	67.9	67.6	67.3	67.7			67.6	0.3
Diameter (mm)	101.5	101.5	101.5	101.6			101.5	0.0

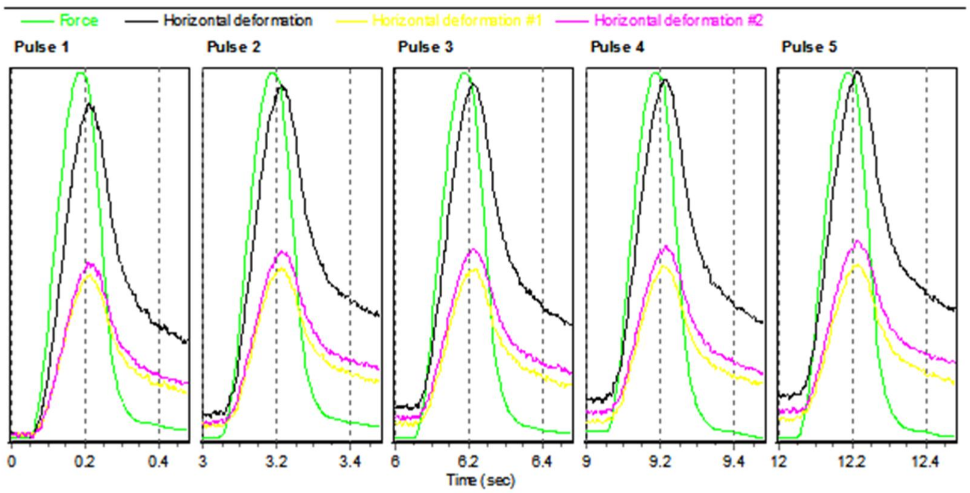
Cross-sectional area (mm²): 8098.1

Test Results

Conditioning pulses: 5
Core temperature (°C): 29.2
Skin temperature (°C): 29.4

Permit horiz1 def'n/pulse (µm): 0.162300

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	6785	6516	6552	6413	6375	6528	143.76	2.20
Total recoverable horiz. deform. (µm)	3.05	3.18	3.10	3.11	3.17	3.12	0.05	1.53
Peak loading force (N)	2089	2092	2049	2013	2039	2056	30.41	1.48
Recoverable horiz. deform. #1 (µm)	1.46	1.54	1.49	1.49	1.54	1.50	0.03	2.07
Recoverable horiz. deform. #2 (µm)	1.59	1.64	1.61	1.62	1.63	1.62	0.02	1.03
Seating force (N)	187	196	188	221	222	203	15.58	7.69



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60 %(C) RAP Resilient Modulus Test Results

Indirect Tensile Modulus Test

Test method: ASTM D4123-82 / AASHTO TP31 (horiz. lvdts only, assumed Poisson's ratio)
Data fileName: E:\New folder\Sample 60C.D003
Template file name: C:\Users\user\Desktop\Templates UTM 2015 april\Dinesh and Aki\Indirect tensile modulus test project August1.P003
Test date & time: 26/08/2015 11:54:14 AM
Project: Evaluation of the strength Characteristics of Recycled Bituminous Pavement
Operator: Athar Asghar
Comments:

Setup Parameters

Target temperature (°C): 25
Loading pulse width (ms): 250
Pulse repetition period (ms): 3000
Conditioning pulse count: 5

Peak loading force (N): 2000
Estimated Poisson's ratio: 0.4

Seating force: AASHTO TP31 (10% of peak)

Specimen Information

Identification: Sample 60C
Remarks...

Dimensions	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Average	Std Dev
Length (mm)	61.2	61.0	61.7	61.9			61.4	0.4
Diameter (mm)	101.3	101.5	101.5	101.6			101.5	0.1

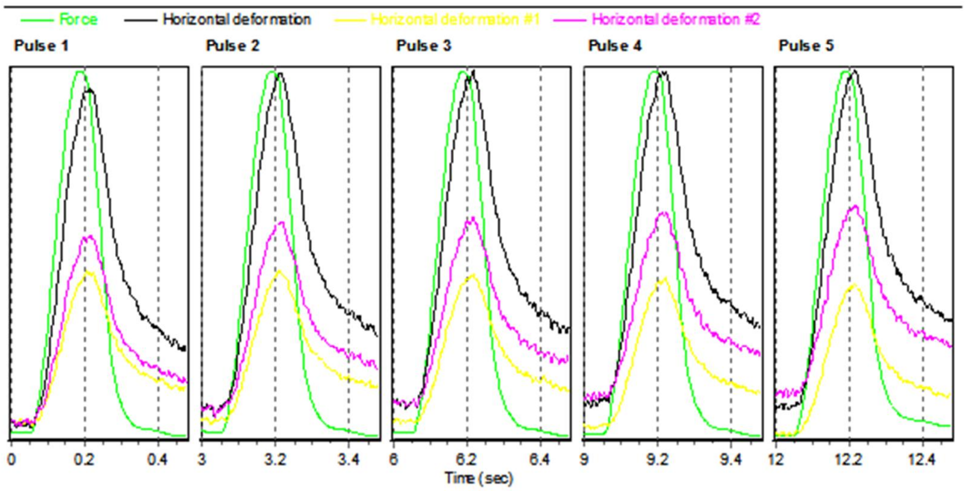
Cross-sectional area (mm²): 8086.6

Test Results

Conditioning pulses: 5
Core temperature (°C): 29.1
Skin temperature (°C): 29.6

Perm't horiz1 def'n/pulse (µm): 0.056370

	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Pulse 5	Mean	Std. Dev.	%CV
Resilient modulus (MPa)	7104	6806	6647	6635	6810	6800	169.16	2.49
Total recoverable horiz. deform. (µm)	3.03	3.11	3.17	3.18	3.17	3.13	0.06	1.79
Peak loading force (N)	1976	1943	1933	1937	1981	1954	20.28	1.04
Recoverable horiz. deform. #1 (µm)	1.39	1.43	1.44	1.48	1.46	1.44	0.03	2.05
Recoverable horiz. deform. #2 (µm)	1.65	1.68	1.73	1.71	1.72	1.69	0.03	1.71
Seating force (N)	209	226	219	223	191	213	12.81	6.00



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Appendix E – Volumetric Properties Worksheets

0% RAP Volumetric Properties Test Worksheet

Compacted Density (Test Method Q306B)			
Pat No. 0% RAP	A	B	C
Height (mm)	60.3	60.9	60.9
Mass sample in Air (g) m1	1155.9	1165.1	1572.3
Mass sample in water (g) m2	685.6	690	940
Mass sample S.S.D. (g) m3	1162.2	1168	1580
Water Temp & Density (pw)	0.9975	0.9975	0.9975
Compacted Density m1*pw/(m3-m2)	2.419	2.431	2.451
Average C.D (t/m^3)	2.434		

Maximum Density (Test Method Q307A)		
Flask No.	D1	D2
Mass Flask (g) m1	1363	1363
Mass Flask + Mix (g) m3	2480	2489
Mass Flask + Mix in Water (g) m4	1426.5	1440
Water Temp & Dendity (Dw1)	0.997	0.997
Mass Flask in water (g) m2	750	748
Water Temp & Dendity (Dw2)	0.997	0.997
Mass Sample A = m3 - m4	1117	1126
Vol.Flask + Sample Vfs = (m4 - m4)/Dw1	1056.67	1052.16
Vol.Flask Vf = (m1 - m2)/Dw2	614.84	616.85
Volume Sample V = Vfs - Vf	441.83	435.31
Max Density t/m^3 A/V	2.528	2.587
Difference (<0.025)	-0.059	
Average M.D. (t/m^3)	2.557	

Voids Calculation (Test Method Q311)	
Bitumen Content B	4.7
Maximum Density Dm	2.557
Compacted Density Dc	2.434
Bitumen Density Db	1.04
Binder Absorption b	0.4
Effective Binder VB = Dc/Db * (B-b+Bb/100)	10.11
Air Voids AV = 100*(1 - Dc/Dm) %	4.8
VMA = VB + AV (%)	14.94
VFB = (100*VB)/VMA %	67.6

15% RAP Test Worksheet

Compacted Density (Test Method Q306B)			
Pat No. 15 % RAP	A	B	C
Height (mm)	71.2	67.6	61.7
Mass sample in Air (g) m1	1420.3	1371.2	1245.9
Mass sample in water (g) m2	825	806	747.8
Mass sample S.S.D. (g) m3	1421.2	1371.4	1246.8
Water Temp & Density (pw)	0.9975	0.9975	0.9975
Compacted Density m1*pw/(m3-m2)	2.376	2.419	2.491
Average C.D (t/m^3)	2.429		

Maximum Density (Test Method Q307A)		
Flask No.	D1	D2
Mass Flask (g) m1	1364	1363
Mass Flask + Mix (g) m3	2553	2583
Mass Flask + Mix in Water (g) m4	1471.2	1494.1
Water Temp & Dendity (Dw1)	0.997	0.997
Mass Flask in water (g) m2	750	748
Water Temp & Dendity (Dw2)	0.997	0.997
Mass Sample A = m3 - m4	1189	1220
Vol.Flask + Sample Vfs = (m4 - m4)/Dw1	1085.055	1092.177
Vol.Flask Vf = (m1 - m2)/Dw2	615.848	616.851
Volume Sample V = Vfs - Vf	469.208	475.326
Max Density t/m^3 A/V	2.534	2.567
Difference (<0.025)	-0.033	
Average M.D. (t/m^3)	2.550	

Voids Calculation (Test Method Q311)	
Bitumen Content B	4.7
Maximum Density Dm	2.550
Compacted Density Dc	2.429
Bitumen Density Db	1.04
Binder Absorption b	0.4
Effective Binder VB = Dc/Db * (B-b+Bb/100)	10.09
Air Voids AV = 100*(1 - Dc/Dm) %	4.8
VMA = VB + AV (%)	14.86
VFB = (100*VB)/VMA %	67.9

30% RAP Test Worksheet

Compacted Density (Test Method Q306B)			
Pat No. 30 % RAP	A	B	C
Height (mm)	63.6	73.5	70.1
Mass sample in Air (g) m1	1243	1428.6	1368.8
Mass sample in water (g) m2	744.2	840	807.7
Mass sample S.S.D. (g) m3	1248.5	1434.3	1372.2
Water Temp & Density (pw)	0.9975	0.9975	0.9975
Compacted Density m1*pw/(m3-m2)	2.459	2.398	2.419
Average C.D (t/m^3)	2.425		

Maximum Density (Test Method Q307A)		
Flask No.	D1	D2
Mass Flask (g) m1	1363.1	1363
Mass Flask + Mix (g) m3	2550.7	2543
Mass Flask + Mix in Water (g) m4	1468.5	1468.6
Water Temp & Dendity (Dw1)	0.997	0.997
Mass Flask in water (g) m2	750	748
Water Temp & Dendity (Dw2)	0.997	0.997
Mass Sample A = m3 - m4	1187.6	1180
Vol.Flask + Sample Vfs = (m4 - m4)/Dw1	1085.456	1077.633
Vol.Flask Vf = (m1 - m2)/Dw2	614.945	616.851
Volume Sample V = Vfs - Vf	470.512	460.782
Max Density t/m^3 A/V	2.524	2.561
Difference (<0.025)	-0.037	
Average M.D. (t/m^3)	2.542	

Voids Calculation (Test Method Q311)	
Bitumen Content B	4.7
Maximum Density Dm	2.542
Compacted Density Dc	2.425
Bitumen Density Db	1.04
Binder Absorption b	0.4
Effective Binder VB = Dc/Db * (B-b+Bb/100)	10.07
Air Voids AV = 100*(1 - Dc/Dm) %	4.6
VMA = VB + AV (%)	14.69
VFB = (100*VB)/VMA %	68.6

40% RAP Test Worksheet

Compacted Density (Test Method Q306B)			
Pat No. 40 % RAP	A	B	C
Height (mm)	63.7	64.5	65.4
Mass sample in Air (g) m1	1279	1283	1312
Mass sample in water (g) m2	773.6	765.4	795.9
Mass sample S.S.D. (g) m3	1290.6	1287.2	1327.9
Water Temp & Density (pw)	0.9975	0.9975	0.9975
Compacted Density m1*pw/(m3-m2)	2.468	2.453	2.460
Average C.D (t/m^3)	2.460		

Maximum Density (Test Method Q307A)		
Flask No.	D1	D2
Mass Flask (g) m1	1363	1363
Mass Flask + Mix (g) m3	2487	2516
Mass Flask + Mix in Water (g) m4	1426.5	1452.6
Water Temp & Dendity (Dw1)	0.997	0.997
Mass Flask in water (g) m2	750	748
Water Temp & Dendity (Dw2)	0.997	0.997
Mass Sample A = m3 - m4	1124	1153
Vol.Flask + Sample Vfs = (m4 - m4)/Dw1	1063.691	1066.600
Vol.Flask Vf = (m1 - m2)/Dw2	614.845	616.851
Volume Sample V = Vfs - Vf	448.847	449.749
Max Density t/m^3 A/V	2.504	2.564
Difference (<0.025)	-0.059	
Average M.D. (t/m^3)	2.534	

Voids Calculation (Test Method Q311)	
Bitumen Content B	4.7
Maximum Density Dm	2.534
Compacted Density Dc	2.460
Bitumen Density Db	1.04
Binder Absorption b	0.4
Effective Binder VB = Dc/Db * (B-b+Bb/100)	10.22
Air Voids AV = 100*(1 - Dc/Dm) %	2.9
VMA = VB + AV (%)	13.13
VFB = (100*VB)/VMA %	77.8

50% RAP Test Worksheet

Compacted Density (Test Method Q306B)			
Pat No. 50 % RAP	A	B	C
Height (mm)	60.3	60.9	66.5
Mass sample in Air (g) m1	1125.8	1201.5	1315.7
Mass sample in water (g) m2	671.1	714.4	781
Mass sample S.S.D. (g) m3	1126.1	1202.8	1316.8
Water Temp & Density (pw)	0.9975	0.9975	0.9975
Compacted Density m1*pw/(m3-m2)	2.468	2.454	2.449
Average C.D (t/m^3)	2.457		

Maximum Density (Test Method Q307A)		
Flask No.	D1	D2
Mass Flask (g) m1	1363	1363
Mass Flask + Mix (g) m3	2496	2515
Mass Flask + Mix in Water (g) m4	1426.5	1452.6
Water Temp & Dendity (Dw1)	0.997	0.997
Mass Flask in water (g) m2	750	748
Water Temp & Dendity (Dw2)	0.997	0.997
Mass Sample A = m3 - m4	1133	1152
Vol.Flask + Sample Vfs = (m4 - m4)/Dw1	1072.718	1065.597
Vol.Flask Vf = (m1 - m2)/Dw2	614.845	616.851
Volume Sample V = Vfs - Vf	457.874	448.746
Max Density t/m^3 A/V	2.474	2.567
Difference (<0.025)	-0.093	
Average M.D. (t/m^3)	2.521	

Voids Calculation (Test Method Q311)	
Bitumen Content B	4.7
Maximum Density Dm	2.521
Compacted Density Dc	2.457
Bitumen Density Db	1.04
Binder Absorption b	0.4
Effective Binder VB = Dc/Db * (B-b+Bb/100)	10.20
Air Voids AV = 100*(1 - Dc/Dm) %	2.5
VMA = VB + AV (%)	12.73
VFB = (100*VB)/VMA %	80.2

60% RAP Test Worksheet

Compacted Density (Test Method Q306B)			
Pat No. 60 % RAP	A	B	C
Height (mm)	66	67.6	61.4
Mass sample in Air (g) m1	1307.4	1358.1	1230.4
Mass sample in water (g) m2	770	805	732.1
Mass sample S.S.D. (g) m3	1306	1358.7	1230.9
Water Temp & Density (pw)	0.9975	0.9975	0.9975
Compacted Density m1*pw/(m3-m2)	2.433	2.447	2.461
Average C.D (t/m^3)	2.447		

Maximum Density (Test Method Q307A)		
Flask No.	D1	D2
Mass Flask (g) m1	1363	1363
Mass Flask + Mix (g) m3	2490	2530
Mass Flask + Mix in Water (g) m4	1426.5	1452.6
Water Temp & Dendity (Dw1)	0.997	0.997
Mass Flask in water (g) m2	750	748
Water Temp & Dendity (Dw2)	0.997	0.997
Mass Sample A = m3 - m4	1127	1167
Vol.Flask + Sample Vfs = (m4 - m4)/Dw1	1066.700	1080.642
Vol.Flask Vf = (m1 - m2)/Dw2	614.845	616.851
Volume Sample V = Vfs - Vf	451.856	463.791
Max Density t/m^3 A/V	2.494	2.516
Difference (<0.025)	-0.022	
Average M.D. (t/m^3)	2.505	

Voids Calculation (Test Method Q311)	
Bitumen Content B	4.7
Maximum Density Dm	2.505
Compacted Density Dc	2.447
Bitumen Density Db	1.04
Binder Absorption b	0.4
Effective Binder VB = Dc/Db * (B-b+Bb/100)	10.16
Air Voids AV = 100*(1 - Dc/Dm) %	2.3
VMA = VB + AV (%)	12.49
VFB = (100*VB)/VMA %	81.3